Application of Unmanned Aerial Vehicles for Surveying and Mapping in Mines: A Review

Long Quoc Nguyen, Minh Tuyet Dang, Luyen K. Bui, Quy Bui Ngoc, and Truong Xuan Tran

Abstract The use of unmanned aerial vehicles (UAVs) is increasing in the mining industry because of the obvious economic and environmental benefits as well as reducing the risk to mineworkers. This paper presents a review of recent developments in relation to the applications of UAVs in surveying and mapping of surface, underground, and abandoned mines. Additionally, after detecting the barriers associated with the deployment of UAV technology in mine surveying, the counter methods to overcome these challenges will be discussed. Finally, the prospects for the development of UAVs are also considered. The results indicate that UAVs can be used for constructing surfaces, creating three-dimensional (3D) models, evaluating their accuracy, and conducting topographic surveying of surface mines. Additionally, this system is a useful tool for mapping underground and abandoned mines. This paper provides a technical reference for expanding the knowledge and recognition of UAV applications in surveying and mapping in mine areas.

Keywords UAV · Drone · Mine · Surveying · Mapping · Terrain surveying

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1 Introduction

Traditional data collection applying a total station is limited by time and safety and thus often leads to a lack of necessary information for monitoring and mapping [1]. Generally, in mine areas, a total station is used for surveying, of which the measurement data are then processed using a computer-aided design (CAD) software. However, this approach is not effective and has many challenges for hard-to-reach areas [2]. The development of 3S technology, i.e., Remote sensing (RS), Global Navigation Satellite Systems (GNSS), and Geographic Information System (GIS), provides a critical technical guarantee for surveying and mapping in mine areas [3]. Although 3S technology can replace traditional ground mapping, RS with low spatial resolution satellite images is susceptible to weather problems, such as cloud cover. Furthermore, the lower temporal resolution makes satellite imagery difficult to depict the characteristics of mine areas undergoing extreme changes [4]. Therefore, this technology cannot meet the requirements of terrain monitoring and surveying in the mine, in particular in a small-scale or newly worked mine. In comparison, an unmanned aerial vehicle (UAV) method is inexpensive and has broader applicability. In other words, one of the main advantages of using UAVs compared to airborne or traditional field surveys is the significantly lower cost of exploration, especially for remote regions with poor infrastructure [5].

The usage of drones in mine areas is seemingly endless because they can assist to acquire data in the field in real time [6]. Most importantly, this tool can provide access to areas that are hard or dangerous to reach, or inaccessible by human workers, such as vertical cliffs or hills, underground mines, and mining regions. Moreover, UAVs are also capable of doing some mining-related tasks faster and at a lower cost, such as terrain surveying and 3D modeling, land damage assessment, and ecological environment monitoring [3]. They are equipped with various sensors, such as spectral imaging sensors, thermal infrared cameras, and gas sensors, which could give necessary data for different monitoring objects in the mining industry [3]. Rathore and Kumar [6] unlocked the potentiality of UAVs in the mining industry and its implications. They proposed the applications that UAV technology can play an important role in shaping the future of mining concepts, including safety and security, productivity, surveying and mapping, and field data collection [6].

In the mining industry, UAV technology is widely used in terrain surveying, 3D modeling, land damage assessment, ecological monitoring, geological hazards, pollution monitoring, and land reclamation and ecological restoration assessment [3]. According to Mukhamediev et al. [5], in the mineral exploration sphere, due to the gradual depletion of the existing field resources, it is necessary to apply new methods that intensify the processes of exploration. Thus, in recent years, the use of UAVs in mining activities is rapidly expanding. The main spheres of UAV application include mapping, 3D modeling, and conducting geophysical research [5]. The primary surface data, such as Digital Surface Model (DSM), Digital Elevation Model (DEM), and orthomosaic images, can be generated by a UAV system equipped with digital cameras [7] with some types of image processing software based on the Structure from Motion (SfM) technique, such as Agisoft Photoscan and Pix4D Mapper. Besides, the obtained surface data not only provides detailed information on the topographical variation but also is important in the calculation of erosion gulley size or slope stability in mine areas [8], estimation of surface extent, and volumetric excavation [7].

Recently, a few scientists have published review papers regarding the UAV application in mining operations. While Park and Choi [9] reviewed the applications of UAVs in mining from Exploration to Reclamation, Shahmoradi et al. [10] performed a comprehensive review to highlight the applications of drone technology in surface, underground, and abandoned mines. Unlike other literature reviews, Lee and Choi presented issues related to UAV technology in mine areas, such as mine surveying, mine operations, drill and blast, mine safety, and construction. Among the applications, using UAVs in terrain surveying and 3D modeling is one of the most popular applications for mining operations. However, no prior reviews have examined to identify and categorize UAV applications related to terrain surveying and mapping mine sites. The goal of this paper is to present a critical review of different applications of UAV in terrain surveying and 3D modeling in mine areas.

2 Data and Methodology

In this study, a systematic review of the extant literature is performed based on a structured analysis of topic-specific studies that is related to terrain surveying and 3D modeling in mine areas.

2.1 Search Terms

The first step of a systemic review is to determine the related key works/individual concepts and operationalize them into search terms and syntax. For this study, they are arranged into the following search syntax for study retrieval: (“Unmanned Aerial Vehicles” OR “UAV” OR “Unmanned Aerial System” OR “UAS” OR “Drone”); AND (“Mine” OR “Mining” OR “Surface mine” OR “Open-pit mine” OR “Underground mine” OR “Abandoned mine” OR “Closed mine”); AND (“Surface” OR “DEM” OR “DTM” OR “DSM” OR “Surveying” OR “3D mapping” OR “3D model”).

2.2 Search Procedure

The review is divided into five sections: defining the research questions, determining relevant studies, choosing studies, charting the data, and collating, summarizing, and reporting the results. A systematic search using the search syntax is performed in the Google Scholar, ScienceDirect, Scopus, and Web of Science databases. The main search language is English. The titles and abstracts of publications are reviewed to determine whether they meet the content of the paper. To be included in this review, the publications are required to be published in peer-reviewed journals or conference papers, issued within the last decade (i.e., 2010 to 2022), and focusing on UAV applications within the mine surveying domain. Some types of studies such as reports or industry trade articles are excluded. In the identification stage, 215 potential related studies are detected. After screening to eliminate duplicate entries, research that was not published within the 2010 to 2022 year range, and non-peer-reviewed papers, 175 documents are carried forward for eligibility analysis. In order to prove the eligibility, the full texts of the papers are reviewed, by which 114 are excluded because they are either not related to the mine surveying domain or do not address UAV applications in mines. A total of 66 articles become the foundation of our systematic literature review.

3 Results and Discussion

3.1 Application of UAVs for Terrain Surveying and Mapping in Surface Mines

Terrain surveying or topographic modeling is one of the applications for the mining industry, and it is used primarily for mineral resources and ore reserve estimation, mine planning, and reconciliation. One of the main sources of uncertainty in mining reconciliation is the topographic model updating [11]. Thus, terrain modeling of mine areas in real time is needed. Nevertheless, the traditional methods for mine surveying are expensive and time-consuming, even though it can take months without feedback from the surveying activities. An alternative way to improve the frequency of topography updating is through the use of image-based surfaces acquired by UAVs and processed by specific software [12]. Drones are a cost-effective, quick, and effective data collection tool for the surface generation, such as DEM, DSM, and digital terrain model (DTM). The use of UAVs for visual surveying as well as the creation of 3D models of mine sites has steadily become relevant. UAV technology can acquire high-resolution images, which are then transformed into 3D surface models (DEM, DSM, and DTM), and can be used for producing topographic maps, calculating excavation volume, and showing the mine site in 3D forms. The literature review shows that some scientists have reported the results of constructing DEM for open-pit mines using UAVs [13, 14], and some authors have used other traditional techniques to test the accuracy of DSM obtained using UAVs [12], or analyzing the accuracy of the DEM derived from photogrammetric processing [1, 2, 15, 16]. Additionally, others evaluated the performance of this technology in 3D modeling applications [17–20].

3.1.1 Construction of Surfaces and Accuracy Assessment

Cho et al. [13]. have verified the applicability of UAV photogrammetry to mining engineering. Aerial photos of the test mine area, which were taken by DJI S1000 with 10 cm resolution, were processed with the Agisoft Photoscan software to generate an orthophoto and DEM model [13]. Similarly, Nghia [21] assessed the possibility of developing 3D models for deep open-pit mines from UAV image data. To achieve this goal, the author used the DJI's Inspire 2 device to take photos at the Coc Sau coal mine. The results indicated that the 3D model established from photographic data by Inspire 2 UAV has met the requirements of the accuracy of establishing the mining terrain map at a 1: 1000 scale.

To quantify the uncertainty created by UAV technology, Beretta et al. [12]. compared a DSM formed by photogrammetry using UAVs with those generated through traditional methods. The results showed that the level of detail given by the UAV photogrammetric techniques proved to be more accurate, denser in information, and faster when compared to traditional methods.

According to Forlani et al. [22], the accuracy of photogrammetrically generated DSMs depends on geometric and physical factors, such as the image scale, ground sampling density (GSD), stereo base-length to object distance ratio, camera network geometry, percentages of strip overlap, the accuracy and distribution of ground control points (GCPs), camera calibration, image processing, image matching, point cloud noise, and outlier removal algorithms. The accuracy of DEM depends on flight height also mentioned by Nguyen et al. [23]. Determining DSM quality is therefore a complex task, because the number of variables involved is enormous, and no single experimental study can encompass all of the relevant aspects [22]. Many studies addressed the accuracy of UAV-generated DSM in different environments. Determination of the number of GCPs to ensure the accuracy of mapping and minimize measurements in the field can be found in Nguyen et al. [2]. Similarly, Long et al. [24] used a Light-Weight UAV to choose the number of GCPs for developing precise DSM in the medium-sized open-pit mine.

Kršák et al. [25] also verified the quality of a DSM in mines, which was obtained photogrammetrically using a low-cost UAV. The resultant models demonstrated that the 3D model is multiple times more detailed than the surface formed from the points surveyed by the total station. In addition, UAS-derived DSMs were compared to field measurements of mining pits in the region to assess the accuracy of UAV-derived pit volume measurements [15]. Chirico and DeWitt [15] indicated that UAV imagery and SfM photogrammetric techniques allow DSMs to be produced with a high degree of precision and relative accuracy, but highlighted the difficulties of mapping small artisanal mining pits in remote and data-sparse terrain.

According to Tien Bui et al. [26], the application of UAV and SfM for complex topographic areas, such as open-pit mine areas, is still poorly understood. Therefore, they investigated and verified the potential application of these techniques for building DSM in open-pit coal mine areas and evaluating its accuracy. Because a DSM should only be used after accuracy assessment, in this project, both the horizontal and vertical assessments were carried out by GCPs measured by a Leica total station in terms of Root Mean Square Error (RMSE). The result showed that the DSM model has high accuracy. It can be concluded that small UAVs and SfM are feasible and valid tools for 3D topographic mapping in complex terrains, such as open-pit coal mine areas. Figure 1 that is reused from shows the use of UAV images for generating the DSM of the Nui Beo coal mine, Vietnam.

Like many scientists, Nguyen et al. [1]. believed that the accuracy of UAV-derived DSMs is influenced by topographical factors in the active surface mines. Thus, they performed an experiment to apply the UAV method to three active coal mines, operating at altitudes from −300 m to 300 m. Accordingly, the effects of topographic factors, such as slope, relative elevation, and number of GCPs, on the accuracy of DSMs constructed by the UAV imagery technique were assessed in the experiment. The obtained results revealed that DSMs were generated at a very high horizontal accuracy, i.e., the cm level.

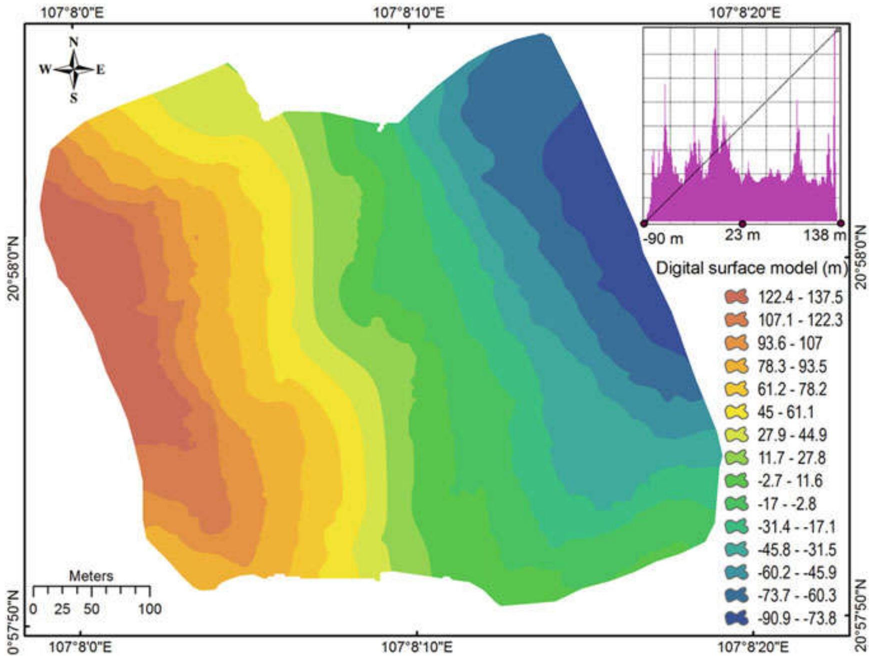

Fig. 1 Digital surface model for the Nui Beo coal mine, Vietnam [26]

In addition, the main topographic information is necessary data for some other purposes. The produced DSM can be used to analyze the progress of the mining process, to estimate ore carrying capacity [27]. Chen et al. [28] examined the characteristics of iron open-pit mines located in Beijing district, China, using high-resolution UAV images. To this end, information regarding DSMs was derived from UAV images and SfM photogrammetry techniques.

Similarly, a spatial query and an analysis of the open-pit mine were performed using the Quantum GIS program and DEMs can be found in the study of Gil and Frąckiewic [29]. In this research, aerial photographs were obtained using a drone by which DTM and DSM were generated. Thereafter, spatial analysis was performed to optimize the location of the observation network points in a surface mine.

Xiang et al. [30] selected an open-pit mine in Beijing, China, as the research area to assess geomorphic changes using a DEM generated using high-resolution UAV images and SfM photogrammetry. Accordingly, the surface of the open-pit mine was analyzed by calculating the difference between the two DEMs.

3.1.2 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. Thus, it is essential to collect accurate data for generating 3D models. Traditional survey methods, which utilize a total station and GNSS receivers to conduct a mine survey, are limited to accurately defining coal stockpiles. Moreover, these approaches increase the risk of injury to the surveyor and demand a high level of safety as well as are often time-consuming, which can lead to additional costs. Alternatively, UAV technology can offer a more cost-effective and safer option [31]. In recent years, UAV photographic measurement technology has played a significant role in 3D modeling in mine areas. Due to UAVs' small size and maneuverability, they can capture data from much lower heights, starting from the ground surface, sweeping through the study areas at various heights and viewpoints, as well as fly-over views above the mine sites [32]. An example of a 3D texture model of the Thuong Tan 3 quarry, Vietnam in 2020 captured by lightweight UAV is shown in Fig. 2.

UAV platforms are increasingly being used as an important source of data for monitoring, surveillance, and 3D modeling of areas influenced by mining activities [17]. They are usually used in combination with digital cameras, and the acquired images are processed using a combination of SfM and Multi-View Stereo (MVS) approaches allowing the extraction of 3D point clouds [33]. The 3D models created from UAV imagery can serve different applications, ranging from natural resource management to civil engineering. Several studies have been carried out in recent years to evaluate the performance of UAVs in 3D modeling applications. Valuable reviews of such studies can be found in [31, 34, 35].

The possibility of 3D modeling in an open-pit limestone mine using a rotary-wing UAV was shown in Kang et al. [36]. The results were used to estimate the amount of mining volume before and after mining of limestone by explosive blasting quickly

Fig. 2 3D texture model of the Thuong Tan 3 quarry, Vietnam in 2020 captured by DJI Phantom 4 Pro

and accurately in a relatively short time. The application of UAVs has been proved as an alternative tool for 3D mapping of open-pit mines in Bui et al. [37]. Based on the UAV images, large-scale 3D topographic maps were successfully modeled. The field test results in this study indicated the applicability of the low-cost UAVs for 3D mapping in large and deep coal pits with relatively high accuracy. This result can be used for optimizing mining operations and also controlling the atmospheric environment.

Similarly, in applying UAVs in building 3D models for large surface mines, Battulwar et al. [18] developed a practical setup to use cost-effective drones for the systematic generation of high-resolution images and 3D models for large open-pit mines. The methods used in this study have been validated using experimental and simulation studies. It can be concluded that the study could generate millimeter resolution 3D models of hazardous inaccessible open-pit slopes without any risks to personnel, who are responsible for the surveys and measurements to obtain multiple parameters of mine slopes.

According to Vassena and Clerici [20], the state-of-the-art 3D surveying technologies, if correctly applied, allow obtaining 3D-colored models of large open-pit mines using different technologies, such as terrestrial laser scanner (TLS) with images combined with UAV-based digital photogrammetry. In the Italian white marble open-pit mine “Botticino”, located in northern Italy, a combination of digital photogrammetry by UAV and TLS was proposed. This resulted in an increase in local precision up to ± 2 cm [20].

Also, Tong et al. [19] processed and integrated point cloud data created by TLS with UAV imagery and generated a 3D model for mapping and monitoring open-pit mine areas, which achieved the decimeter-level accuracy. Besides using software to create 3D models, such as Agisoft and Pi4D, many studies have shown that integrating UAV data into a GIS environment is an appropriate approach for creating 3D models and post-processing of UAV imagery data. Filipova et al. [38] dealt with UAV data integration into GIS and conducted a spatial analysis to generate a 3D model of an open-pit quarry. UAV digital images as well as contemporary photogrammetric techniques help create accurate geometric 3D models. Through 3D model analysis, more precise information about the current processes and events in the quarry could be gathered, leading to future managerial decisions.

Regarding the UAV's application in building 3D models, Tscharf et al. [39] presented a fully automated end-to-end workflow to obtain precise and geo-accurate reconstructions, especially for complex environments such as open-pit mines. Together with aerial images from a UAV, they were able to enrich 3D models by combining terrestrial images and inside views of an object by joint image processing to generate detailed, accurate, and complete reconstructions.

Ulusoy et al. [40] have used a lightweight drone to collect digital aerial images of an open-pit mine for the ultimate purpose of modeling the terrain using the SfM procedure. They have been able to derive a high-resolution (0.3 m/pixel) DEM and a very high-resolution (0.04 m/pixel) orthorectified aerial photograph. The elevation model dataset has been compared with the regular topographic point measurements of the mine pit, and the accuracy of the aerially derived model has been investigated.

Le Van et al. [41] acquired images in open-pit mines using a post-processed kinematic (PPK) drone and produced a highly accurate DSM. In addition, they experimentally proved the possibility of topographic survey for open-pit mines using drones by analyzing the accuracy improvement based on the increased number of GCPs.

According to Shahbazi et al. [35], UAV-based images have the potential to provide data with unprecedented spatial and temporal resolution for 3D modeling. Thus, they presented theoretical and technical experiments regarding the development, implementation, and evaluation of a UAV-based photogrammetric system for precise 3D modeling in the grave-pit mine. The study was preliminarily assessed for the application of gravel-pit surveying by UAV.

The accuracy of a UAV-based 3D model was mentioned in many studies. Park et al. [31] compared the accuracy of UAV-generated 3D coal stockpile models against traditional field survey techniques. They assessed the effect on the accuracy of the coal stockpile for varying shapes**.** The results revealed that the UAV-derived 3D models show maximum volume errors of less than 9.0% and minimum volume errors of more than 0.3%. The accuracy of the 3D model reconstructed from UAV images was also assessed by Park et al. [31]. Wang et al. [34] determined the accuracy of 3D geometry from low-attitude UAV images at the Zijin Mine in China. They implemented different algorithms, such as the SfM and the patch-based multiview stereo (PMVS) systems, to create a dense 3D point cloud from the UAV images. They used 17 GCPs to geo-reference a 3D reconstruction point cloud, and the accuracy of the 3D geometry was evaluated by using both the GCPs and the TLS point cloud. The UAV point cloud accuracy was first evaluated at a point level by comparing the absolute coordinates between the UAV point cloud and the GCPs.

In relation to the accuracy assessment of the UAV-derived 3D model, González-Aguilera et al. [16] indicated that even though the image-based modeling workflow requires applying several steps sequentially in order to obtain a real-based 3D model, and thus, error propagation must be mandatory, the level of obtained accuracy is good enough.

3D mapping is a very important aspect of the mining industry. In recent years, the use of UAVs for visual surveying as well as the generation of 3D images of mine sites has steadily become popular. At present, UAV technology has been used widely in the mining industry for terrain surveying. Drones can acquire high-resolution images that are then transformed into 3D surface models. These models are used for topographic mapping or for showing the mine sites in the 3D form. UAVs equipped with low-cost cameras can be considered a great instrument to survey the surface mine. This photogrammetric approach could overcome the low resolution of satellite images and avoid the tiring groundwork of the total station and Global Positioning System (GPS), as well as provide a 3D visualization effect of the study area [3].

Katuruza and Birch [42] used UAV technology in opencast highwall mapping in opencast mines at Isibonelo Colliery of South Africa to produce data for updating geological models and avail the latest information for mine planning to improve the short-term plans. With the UAS, it is possible to obtain digital images of the highwall as well as a multitude of digital terrain points, all in 3D space. The obtained results indicated that the greater the amount of collected high-resolution images, the more detailed the model produced, a dense 3D image of the pit. The generated drone data model was validated against the resource model and actual survey data.

Malpeli and Chirico [43] explored the application of a small UAS for mapping informal diamond mining sites in Africa. They found that this technology provides aerial imagery of unparalleled resolution in a data sparse, difficult to access, and remote terrain. The aerial images were used to develop 10 cm resolution DEMs of the mine site. The authors used ortho-images and DEMs to model the geomorphology of the terrain, and the areas of diamond deposition in the region could be identified.

According to Leo Stalin and Gnanaprakasam [44], a mine map can give information to optimize mining activity. Regular updating of the 3D model and digital mine maps provides an easy way to assess the activity carried out inside the mine. They used Quadrotor UAV to acquire nadir and oblique aerial images. These images are processed in various UAV data processing software to produce high-resolution orthophotograph, DTM, DSM, contour, and 3D virtual reality models. The digital orthophotograph and 3D models generated from this method were used to create the mine map.

Salvini et al. [45] used UAVs to map fractures in a marble quarry and, subsequently, to build 3D discrete fracture network models. Based on the combined use of high-resolution UAV images and engineering geological data on a marble buttress, the construction of a reliable 3D rock mass model can be done. Preliminary results revealed the benefit of modern photogrammetric systems in producing detailed orthophotos and the latter allows accurate mapping in areas difficult to access (one of the main limitations of traditional techniques).

Several literary studies have been conducted to use fixed-wing and rotary-wing UAVs for terrain surveying in surface mines. According to Lee and Choi [46], there are various characteristics between the fixed-wing and rotary-wing UAVs, such as flight height, speed, time, and performance of mounted cameras; thus, they compared the results of topographic surveying at the same site. The fixed wing showed a relatively negligible error when the results of the two types of aerial surveying were compared with ground data. Figure 3 shows orthomosaic images and DSMs of the study area for the two types of UAVs.

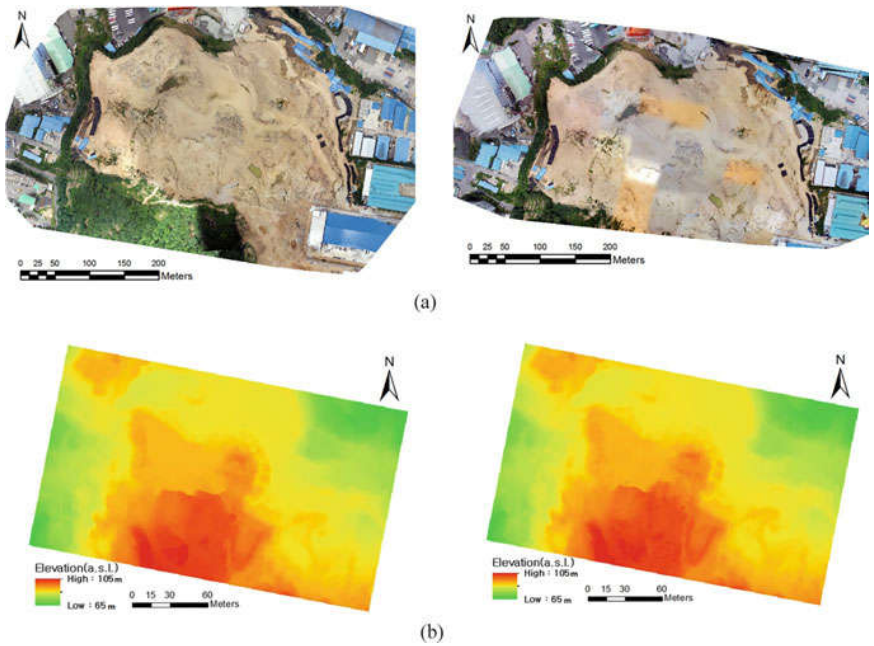

Fig. 3 Results of topographic surveying for the two types of UAVs from [46]: **a** Orthomosaic image, **b** digital surface model

3.2 Application UAV in Terrain Surveying

Besides, some scientists carried out the topographic survey at an open-pit mine using a rotary-wing UAV (DJI Phantom2 Vision+) [47] and a fixed-wing unmanned aerial vehicle (SenseFly eBee) [48]. The obtained results revealed that the fixed-wing UAV has a relatively longer flight time and larger coverage area than rotary-wing UAVs, it can be effectively utilized in large-scale open-pit mines as a topographic surveying tool while rotary-wing UAV is suitable for topographic survey at small-scale open-pit mines [48].

Rossi et al. [49] presented a method to reconstruct the quarry terrain in Bari, Italy, by using nadir and oblique aerial photographs acquired from a UAV and conducted a feasibility analysis after that. It observed that the final position of the point clouds, which show the main geometrical characteristics of the quarry in the topography reconstruction of the study site, can achieve an accuracy of a few centimeters.

In open-pit mines, monitoring of topographic and volumetric changes through time plays an important role in supporting excavation stages and planning rehabilitation strategies. Esposito et al. [7] used UAV photogrammetry to quantify the excavated volume at the Sa Pigada open-pit mine in Sardinia, Italy, and to evaluate the variations in the surface mine extent. They carried out two UAV-based surveys in 2013 and 2015, and 3D dense point clouds and digital orthophotos were obtained by means of the SfM technique. Results obtained in this study suggested that the applied UAV techniques are suitable for performing accurate change detection analysis in an open-pit mine extent.

3.3 Application UAV in Terrain Surveying in Underground Mines

Underground mining shows many accessibility challenges. Mining in deep and high-stress conditions inherently relates hazards to both personnel safety and the mining operations. Due to their small size and maneuver ability, UAVs have various potential applications in underground mining. This may allow them to access locations within a mine that are normally inaccessible, including ore passes, stopes, ventilation raises, and hazardous areas. Nowadays, the application of drone technology in underground mines is in its infancy. There are few UAVs and instruments that are dedicated to underground mines, where we have low-visibility conditions, confined openings, magnetic interference, and an absence of GPS coverage. However, UAV systems are equipped with high-resolution cameras, light emitting diode (LED) lights, and thermal sensors, and thus, useful information can be obtained in areas that are difficult to be accessed by mine workers [9]. In the view of Mitchell and Marshasll [50], the most likely near-term applications for underground UAVs include mine surveying, search, and rescue. In this paper, we only review the studies on UAV application for surveying and mapping of underground mines.

3D map plays an important role in underground mining because it provides accurate data and models of the 3D area of the underground mine. In underground mining, the shape of the underground mine area is dynamic due to a lot of reasons, like the excavation of new tunnels or some natural factors. The accurate and up-to-date 3D model and data of the underground mine environment are, therefore, necessary for an efficient and safe mining process [10]. Li et al. [51] considered the application of UAVs in underground mine mapping and proposed a 3D tunnel system search and mapping algorithm. The tunnel area search and map building are autonomous, and an operator only needs to start or stop the map building in the remote computer. Additionally, a study by Ge et al. [52] presented the results of the work performed by applying UAVs for Tahmoor underground mines in New South Wales (NSW), Australia. They used a UAV to map the underground mine subsidence in these mines. UAV oblique photogrammetry can obtain the three-dimensional (3D) coordinate information of ground features.

Photogrammetry is becoming a more common method for mapping geological and structural features in underground mines. Russell et al. [53] implemented an experiment with photogrammetry conducted from a UAV platform in an underground mine. They assessed the viability of using UAV-based imagery and photogrammetry to model and map rock masses that are inaccessible in underground mines. The obtained results include 3D digital photogrammetry models created from video frame stills and discontinuity map within the digital model.

An interesting example of using an inspection drone in an underground mine for mapping or exploration can be found in the study of Papachristos et al. [54]. They proposed an integrated approach for autonomous navigation and mapping in underground mines using a drone. Stereo cameras have been used for 3D mapping with aerial robots in subterranean tunnels. The research has shown that the usage of long-wave infrared of the electromagnetic spectrum allows the use of thermal cameras in environments with poor visibility and has been included in sensor sets in various underground mapping and localization studies.

According to Turner et al. [55], the advent of inexpensive, open platform UAVs allows to characterize hazardous rock masses by using traditional photogrammetric and forward-looking infrared imagery techniques. In order to prove this, they created a 3D model by thermal imagery using a UAV in an underground mine Barrick Golden Sunlight, Whitehall, Montana, USA, and acquired the geological data from photogrammetry models. The UAV system used in this study included obstacle detection, lighting, thermal imagery, and software. Results concluded that the combination of off-the-shelf technologies with a UAV system can be successfully employed as a geotechnical tool in the underground mining environment.

Similarly, Turner et al. [56] also proved that both thermal and multispectral imaging were successful in the detection and characterization of loose, unstable ground, and adverse discontinuities in the underground mining environment. The datasets, including multiple thermal, multispectral, red, green, and blue (RGB), and Light Detection and Ranging (LiDAR), were acquired in the same study area. They used these data to generate georeferenced 3D point clouds and meshes, and to map discontinuities. Figure 4 shows the DJI Wind 2 in the study of Tuner et al. [56], which could carry a large payload, including a MicaSense RedEdge-M imager, StratusLED ARM lighting, and, most importantly, an Emesent Hovermap SLAM system.

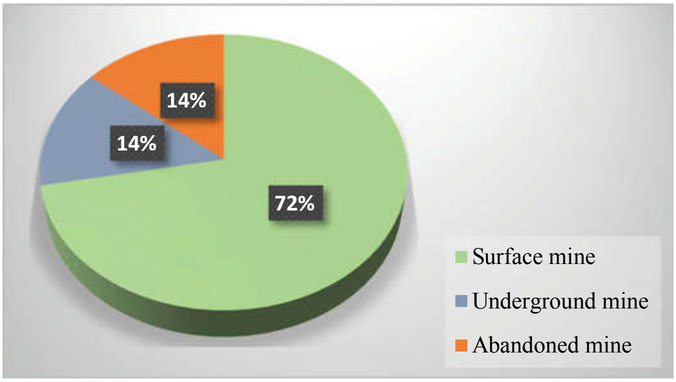

Fig. 4 Percentage distribution and number of reviewed studies of UAV applications in surface, underground, and abandoned mines to surveying and mapping process

3.4 Application of UAVs in Terrain Surveying of Abandoned Mines

Mine survey is an indispensable part of the ecological restoration design of an abandoned open-pit mine because it provides precise survey data for mine management. Furthermore, monitoring and mapping closed mines play an important role to decrease the risk of environmental hazards. However, it is difficult to survey the vast areas with traditional, labor-intensive, expensive monitoring methods. Drone technology, as a financially efficient approach, can be an alternative solution [10]. The most notable recent research effort is by Dai and Xu [57]. In this study, the authors applied UAV photogrammetry technology to 3D modeling and earthwork calculation to solve the problems of high cost, low efficiency, and high labor intensity in traditional manual field mine surveys in the abandoned quarries in Baitu, Suzhou City. 82 ground control points were set up, and elevation data of the ground were acquired using a Dajiang spirit 4 RTK UAV and extracted from a 3D model created with the Context Capture software.

At present, the recultivation of abandoned open-pit mines is a critical environmental task [58]. It is necessary to determine the amount of soil required for the preparation of the investment's expenditure plans. To achieve this, Molnar and Domozi [58] created a 3D surface model based on photogrammetry and UAV photos. As a result, the amount of filling material needed for the recultivation of a closed mine was calculated by 3D models. They matched the volume data computed from geodetic surveys on the mine with UAV-based DSM and the calculation results with the help of the 3D elevation model. The evaluations have indicated that the calculated volume based on photogrammetry has been within the expected accuracy range.

Suh and Choi [59] employed UAV photogrammetry to survey abandoned mine areas. A digital georeferenced orthoimage and DTM with the 5 cm resolution could be obtained by coordinates of pre-installed ground control points (GCPs). Accordingly, contour lines (at the 10 cm contour interval), slope, and curvature were created using the DTM. Validation using the GCP locations showed an error of approximately 14 cm in the generated DTM, which was considered acceptable for subsidence mapping purposes.

Motyka [60] applied photogrammetry for mapping the anthropogenic terrain alterations on exampled closed coal mines in Katowice for land reclamation. In this study, a new UAV platform was proposed for remote laser scanning of terrain from a low altitude, which consisted of an inertial system, a 2D laser scanner, and a system recorder. Moreover, the author presented a mapping of places where some invasive plants exist. Obtained results recommended that, in conditions of difficult geometry of anthropogenic forms requiring constant changes in the UAV flight altitude, it is essential to utilize a parallel system of spatial orientation, such as on-board inertial sensors with GPS.

According to Martin et al. [61], mining of uranium mineral veins in Cornwall, England, has resulted in a significant amount of legacy radiological contamination spread across numerous long-disused mining sites. A newly developed terrain-independent UAV carrying an integrated gamma radiation mapping unit was used for the radiological characterization of a single legacy mining site. It was possible to produce high-spatial-resolution maps, accordingly, determining the radiologically contaminated land areas and rapidly identifying and quantifying the degree of contamination and its isotopic nature. The obtained results showed that the instrument can be considered a viable tool for the characterization of similar sites worldwide.

In order to detect changes in topography linked to anthropogenic and meteorological effects rapidly and precisely and rehabilitate the abandoned mine, Yucel and Turan [62] created 3D terrain models of the mine lakes using high-resolution images from an UAV. 3D modeling of UAV images was performed with the Agisoft software using the most common SfM algorithm. Its workflow, relating to image matching, georeferencing, digital elevation modeling, orthomosaics, 3D point cloud, and 3D textured model creating, was used to create a 3D terrain model for the mine lakes. The study compared the results of two different methods (digitization and classification) within the ArcGIS package. The obtained results proved to be an effective method of visualizing such effects over the short term.

According to Neumann et al. [63], when a coal mine is closed, the methane emission is decreased but does not completely stop. Abandoned mines can release methane at a near-steady rate for an extended period of time. Flooding in the mines can prohibit gas emissions and buildups in empty spaces. This can help to mitigate the dangerous level of working in nearby active underground mines. In their study, based on micro-drone, the author created a 3D virtual mine map from 3D point cloud of optical sensors to calculate the volume capacity for gas storage in abandoned mines.

4 Results and Discussion

In this paper, 69 research publications that encompassed the application of UAVs within surveying and mapping in mine sites were reviewed. Figure 4 shows the percentage distribution of UAV application in three types of mines and the number of studies classified for each type. Table 1 indicates the application in surface mine, underground mine, and abandoned mine and the corresponding number of studies.

As shown in Table 1 and Fig. 4, more than 70% of UAV research were applied to terrain surveying and mapping in surface mines (36/50 research). UAVs were used mainly to generate surfaces, create 3D models, assess their accuracy, and survey terrain in these mines. Of the 36 articles, 13 discussed UAV applications to creating 3D models and evaluating their accuracy, and 14 reported the use of UAVs in the construction of surfaces and assessment of their accuracy. A topographic survey of surface mines based on UAV images can be found in nine studies. Despite advancements in UAV technology, the use of drones in underground mines has been limited. This is reflected in the number of studies applying this technology to survey and

Table 1 UAV application in terrain surveying of surface, underground, and abandoned mines

No	Mine type	Applications	Resources	Numbers
1	Surface mine	Construction of surfaces and assessment their accuracy	[1, 2, 12–15, 22, 23, 25, 26, 28–30, 64]	14
2		Creating 3D models and evaluating their accuracy	[16, 18–20, 31, 34–41]	13
3		Topographic survey	[7, 42–49]	9
4	Underground mine	Mapping 3D in underground mines	[51–56, 64]	7
5	Abandoned mine	Mapping in abandoned mines	[57–63]	7
Sum				50

map the underground mines with only seven research. All these studies focused on generating a 3D model to support an efficient and safe mining process. With the same number, the application of surveying and mapping in closed mines using UAVs was mentioned in seven publications. Of those, six papers conducted research in surface mines and only one studied in underground mines. Notably, while the reviewed research on the application of UAV in surveying and mapping of open-pit mines can apply the rotary-wing or fixed-wing UAV type, all reviewed literatures on UAV applications of surveying in underground mines used UAVs of the rotary-wing type. Thus, it seems that more efforts should be done to improve terrain surveying and mapping in the integration of UAVs with the mine industry.

5 Current Limitations and Future Perspectives in the Use of UAVs for Surveying and Mapping in Mine Sites

5.1 Current Limitations

To our knowledge, this is the first comprehensive scoping review of UAV applications in terrain mapping and surveying of mine sites. Almost all existing review papers have not discussed terrain surveying specifically and are based on a broad search without utilizing a structured approach for literature review, which may result in the omission of related publications. At the moment, it is difficult to perform a systematic review due to the scarcity of experimental studies in the mine areas, in particular, underground and abandoned mines as well as the lack of standardization of mine drones. However, this review followed a structured methodology that includes the application of drones in different types of mines, i.e., surface, underground, and abandoned mines. Therefore, this paper may be the most in-depth review of UAV applications in mine mapping and surveying.

As highlighted in this literature review, UAV technology has been successfully deployed in surveying and mapping mine sites. Although these UAV applications in the mine industry are expanding, there are several obstacles to the more widespread adoption of drone in the mining sector beginning with technical limitations, such as limited battery capacity, flight time, payload, sensor sensitivity, and dependence on climatic conditions. These obstacles affect the different extents of performing the tasks with UAV usage [5]. In surface mines, weather conditions pose a challenge by inducing deviations in the drone's predesignated paths compared to underground mines. In some situations, the weather can affect the UAV system, leading to the failure in their missions [65].

Besides, there are some difficulties in using UAVs in underground mines. In this working environment, mineworkers are always faced with harsh conditions, such as confined space, heat and humidity, dusty concentration, air velocity, poor lighting, lack of wireless communication system, magnetic interference, and an absence of GPS coverage [9, 66]. This leads to an extreme difficulty for an operator to perform a fly by drone in the underground mine. There are few UAVs and instruments that are dedicated to underground environments [9]. Therefore, it is necessary to design an optimized micro-drone that can solve all of these challenges. According to Shahmoradi et al. [10], ideally, the drone should be able to identify and avoid obstacles during its flight in the indoor environment. One of the types of microdrones is multirotor, which allows them to fly in confined spaces, such as underground mines, because they can hover and have high maneuverability. Furthermore, Shahmoradi et al. [10] also designed an autonomous spherical micro-drone for underground mine environments. They proposed a design of optimized multi-rotor UAVs made mainly from carbon fibers, which can reduce the differences for using drones in underground mine environments. In Fig. 5, a schematic view of designed drones for underground mine applications is shown [66, 67]. In addition to these studies, Park and Choi [9] showed that if UAV systems are equipped with high-resolution cameras, LED lights, and thermal sensors, necessary information, such as image (thermal, spectral, etc.), distance, inertial measurement unit, and sound navigation and ranging data, can be acquired in areas where are difficult to be accessed by mine workers.

Another drawback stems from UAV legal restrictions. UAV flights should also adhere to the related legislation and national rules. Moreover, software and algorithmic limitations include restrictions in data processing, while obstruction of software tools and algorithms for UAV control and flight planning are other prohibitive factors [10]. Furthermore, endurance ability has always been a disadvantage point for the UAV industry, in particular for mine applications. Thus, batteries with more endurance should be considered in the future. Also related to this limitation of the UAVs, Tong et al. [19] found that UAVs need more flights to cover a large area due to their low endurance. This is undoubtedly a challenge for remote regions without continuous power supply, such as quarry or abandoned mines.

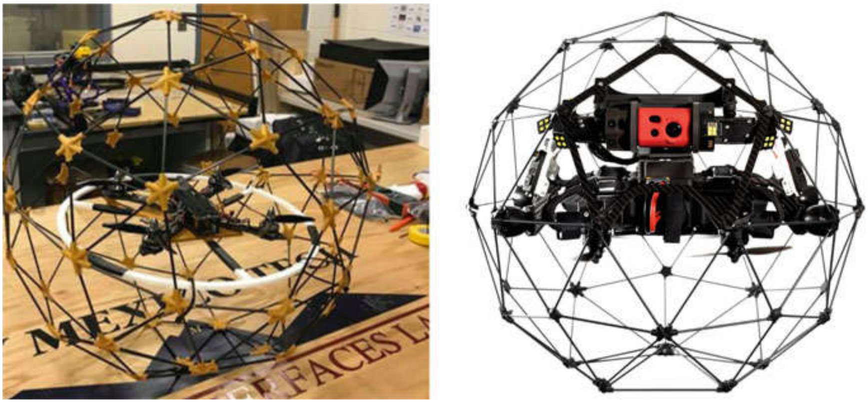

Fig. 5 Designed spherical drone for underground mine applications [66, 67]

5.2 *Future Prospects*

Although there are some obstacles, it can be found that UAVs have been shown to have great prospects for application in surveying and mapping in mine areas. They can replace traditional measurements, perform previously time-consuming tasks rapidly, and acquire periodic data with a much better resolution than satellite images [68]. UAVs in mines have potential applications in surface measurement, such as surface mapping, 3D reconstruction, and terrain surveying. The images from UAVs using laser scanners and high-resolution cameras can be utilized for generating high definition, geographically accurate 3D models, such as DEM, DTM, and DSM. Moreover, these images are converted in point cloud form, which in turn can be conducted to create maps for rock mass stability analysis, calculation of mining subsidence.

Besides, underground mines are one of the most dangerous aspects of the mining industry, and therefore, there are various applications of UAVs to improve safety, including surface roughness mapping, stability analysis, ventilation modeling, hazardous gas and leakage detection, and coal fire detection. In addition, accurate underground terrain mapping could help surveyors master downhole information to provide a plan for further mining activities [10].

The environment of mine areas varies drastically and rapidly. Therefore, in the view of Ren et al. [3], a single data source is usually insufficient to meet the requirements of the actual work. The matching and the integration of multi-source data can achieve complementarity by taking advantage of other methods' strengths. Furthermore, UAV and artificial intelligence (AI) technology have a significant impact on mining activities. Jung and Choi [69] conducted a systematic review to examine the current trends in machine learning research related to the mining industry and analyzed previous studies in the specific subject areas. Thus, it is necessary to integrate AI technology and UAVs in surveying and mapping in mine areas for future research.

6 Conclusion

In this paper, the drone applications in the mining industry for surveying and mapping have been discussed through publications conducted in the past 10 years. The review analyzed 50 papers related to survey and establishing mine topographic maps by UAVs, which were published in academic journals and M.Sc/Ph.D theses. The results revealed that the application of UAVs in mine surveying can be performed in surface, underground, and abandoned mines. As demonstrated in this review, drones are an excellent tool for mapping, surveying, constructing surfaces, and creating a 3D model of mines. Fixed-wing and rotary-wing drones are the most commonly used ones in surveying surface mines, while rotary-wing drones are preferable for underground mines. The obtained results have indicated that UAVs show the benefits of being operable at a low cost and the ability to work in areas difficult to access. Because the UAV system can fly at low altitudes, compared to a manned airborne method or satellite method, the UAV-based approach can capture high-resolution images with dense density.

Despite significant advancements in UAV technology, there are some limitations for the applications of drones in underground and abandoned mines. This is due to many challenges, such as harsh environments, lack of wireless signal, confined spaces, and the concentration of dust and gases. The possible solution for the use of drones in underground mining was mentioned in the review. Encased drones with rotary wing are suggested as a solution to overcome the obstacles in underground mine environments. In the future, the integration of UAV and AI technology promises to bring many useful applications for surveying and mapping in mine areas.

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