*drones*

*Review*

# A Comprehensive Review of Applications of Drone Technology in the Mining Industry

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**Abstract:** This paper aims to provide a comprehensive review of the current state of drone technology and its applications in the mining industry. The mining industry has shown increased interest in the use of drones for routine operations. These applications include 3D mapping of the mine environment, ore control, rock discontinuities mapping, postblast rock fragmentation measurements, and tailing stability monitoring, to name a few. The article offers a review of drone types, specifications, and applications of commercially available drones for mining applications. Finally, the research needs for the design and implementation of drones for underground mining applications are discussed.

**Keywords:** drones; remote sensing; surface mining; underground mining; abandoned mining

## 1. Introduction

Drones, including unmanned air vehicles (UAVs) and micro air vehicles (MAVs), have been used for a variety of civilian and military applications and missions. These unmanned flying systems are able to carry different sensors based on the type of their missions, such as acoustic, visual, chemical, and biological sensors. To enhance the performance and efficiency of drones, researchers have focused on the design optimization of drones that has resulted in the development and fabrication of various types of aerial vehicles with diverse capabilities.

The use of aerial vehicles for industrial applications goes back to the 19th century. In 1860, balloons were used to take pictures for remote sensing purposes [1]. In 1903, pigeons carrying a breast-mounted aerial camera were used for photography [2]. Around the beginnings of World War I, aerial torpedoes, which are known as the origin of drones, were developed [3,4]. In recent years, attention to research and development of unmanned aerial vehicles has been growing by academic and industry communities worldwide [5,6].

Depending on the defined mission, drones are generally classified widely based upon their configurations [6]. Drones can be grouped into nine categories, such as fixed-wing, flapping wing, rotary-wing, tilt-rotor, ducted fan, helicopter, ornithopter, and unconventional types [6].

Drones have a variety of capabilities for both military and civilian utilization [6–10]. These capabilities, along with the demand for unmanned technologies, has resulted in the integration of drones into civil practices [11]. Toward this end, new unmanned aerial vehicles are being developed that can perform various missions in a variety of environments [11,12]. For example, drones are utilized in a vast range of civilian applications such as search and rescue, surveillance, firefighting, weather monitoring, surveying [13], power infrastructure monitoring [14], and urban planning and management [15]. Drones have also been used for building environment monitoring [13] and urban traffic monitoring [16,17], ecological and environmental monitoring [18], species distribution modeling [19], population ecology [19], and ecological monitoring and conservation [20]. Archeology and cultural heritage [21], human and social understanding [22,23], personal and business drones for photography and videography, and even delivery services [13] are other applications of drones. In addition, the unmanned aerial systems have been successfully used in different industries, such as agriculture [24], oil, and gas [25], construction [26], environmental protection [27], mining [18], etc.

Recently the mining industry has shown increased interest in the use of drones for routine operations in surface and underground mines [28–33]. This study aims to conduct a review of the application of drone technology in the mining industry. For this purpose, previous studies and information from the companies that provided drones for mining industries are explored. In this paper, the applications of drones in surface and underground mines are reviewed. Applications of drones in surface and underground abandoned mines are also highlighted. Furthermore, the commonly used sensors on mining drones are presented. The challenges in using drone technology in underground mines and potential solutions to those barriers are discussed.

## 2. Drone Technology Applications in the Mining Industry

There are two main advantages of using drones in mining operations [28]. First, drones equipped with different types of sensors can conduct a quick inspection of an area, either in an emergency situation or hazard identification. Second, inspection and unblocking of blocked box-holes and ore-passes can be done using drones. Drones can also be used for blockage inspection, explosive, and package delivery. Lee and Choi categorized the applications of drones in the mining industry, including surface, underground, and abandoned mines, as demonstrated in Table 1 [18].

**Table 1.** The applications in mining [18].

| Surface Mine | Underground Mines | Abandoned Mines |
|---|---|---|
| • Mine operation<br>• 3D mapping<br>• Slope stability<br>• Mine safety<br>• Construction monitoring<br>• Facility management | • Geotechnical characterization<br>• Rock size distribution<br>• Gas detection<br>• Mine rescue mission | • Subsidence monitoring<br>• Recultivation<br>• Landscape mapping<br>• Gas storage detection<br>• Acid drainage monitoring |

## 3. Applications of Drones in Surface Mining

Generally, mines are located in vast and remote mountainous areas. This makes the monitoring of mines and associated infrastructures a challenging task requiring extensive manpower [23]. Therefore, monitoring mines by traditional methods are time and cost consuming [34]. Appropriately, drones can be beneficial in monitoring, surveying, and mapping of mines' environment [23]. Drones can be applied to monitor activities in the mines and topography changes of the mining area, which can lead to a guideline for mine planning and safety [23].

For example, in [23], a drone equipped with a hyperspectral frame camera was used to monitor the safety of the production pit [23,35]. In open-pit mines, optimization of slope angle has an important role in production cost reduction, mine efficiency, and recycling resources [36,37]. Tong et al. used integration of terrestrial laser scanning and drone photogrammetry to investigate slope zones by monitoring point displacement and 3D mapping of open-pit slope zones. They also did monitoring for mine inventory and changes in mine area [23,37].

One of the main challenges in the mining industry is collecting geotechnical data from difficult or impossible to access regions [38]. In addition, mapping discontinuity for slope stability could be done by terrestrial LiDAR methodology. However, "shadow zones" or gap in data is repeatedly produced, due to the small scan angle of LiDAR technology [38,39]. However, drones can be utilized to take photos and make measurements by using the analysis of overlapping photographs [39,40]. McLeod et al., in 2013, did an investigation in an open-pit mine to find the direction of discontinuity on the surface of rock slope by using drones topographical survey [29].

Another challenge in the mining industry is mapping engineering geology of the site. Engineering geology covers mapping outcrops, strikes, dips, features notation, and names that bring about the characterization of the site [41]. Drones are able to take detailed images from outcrops [41–43]. Nevertheless, most of the time, the results need to be checked by a human survey [41,44]. New algorithms in image processing allow one to identify the type of rocks, strike, faults, and dips which decrease the manual workload significantly [41,45–48].

One of the activities that is normally repeated in the mining industry is blasting. Blasting is always involved with safety risks, which could be inspected by drones [33]. Important parameters in blasting design are rock type, geology, topography, geometry, borehole location, etc. which can be controlled by drones [49]. In addition, new low-cost data is available by using drones in blasting operations. Medinac et al. used drones to analyze the rock block size before and after blasting [50]. In another case, drones were put to work for monitoring dust particles after blasting operation in an open-pit mine [51].

Additionally, dust particle of mining activity and tailings has a significant environmental issue on the neighboring environment of mine areas, which can be reduced by monitoring and controlling the moisture of the mine and mine tailings [23]. In [52], thermal sensors are installed on drones to capture changes in the spatial and temporal surface moisture content in iron mine tailings. However, analyzing the relationship of moisture content and mine tailings managing could be helpful in mine tailings management [23].

Adopting drones to the mining industry can ease automation by providing visual and various types of sensing data. Considering excellent maneuverability and low-cost and maintenance [30], drones can make a huge benefit to the mine by surveying large areas in a short period of time compared to traditional methods that used the human workforce [53]. They can provide required data where there are health and safety hazards like in slopes [51] or unstable cavities. Therefore, it makes mines a safer workplace compare to the past.

In 2018, Rupprecht and Pieters proposed a drone to fly over the area for reopening of an old abandoned mine in South Africa. The drone was financially evaluated, and its sensitivity and risk were assessed. The used drone was able to take pictures of the whole targeted mine, which also included images of damages and infrastructure [31].

In the University of Queensland, drone technology was used to investigate the characterization of blasting plumes. Drones could measure blasting plumes with a concentration of 1 mg/m3 accuracy. The air quality sensor and autopilot data were integrated to produce an airborne particulates characterization in time and space, which had not been accessed without using a drone. The challenging part of this research was selecting a sensor for dust monitoring using drones [54].

In [29], a drone was used to measure fracture orientation in an open-pit mine. This research was done in three main steps. First, the drone took pictures of the fractures. Second, three dimensional (3D) point cloud (a set of the data point in the space is called point cloud) were produced by using structure from motion (SFM) software. Third, an image processing algorithm was generated to estimate fracture orientation in an open-pit mine. They used a multirotor drone, called Aeryon Scout, to carry a 100-gram camera for taking videos and images.

In 2013 the Aeryon Scout drone was used to obtain a three-dimensional point cloud of the surface mine. In this research, the battery was installed on the top of the drone, and the payload was at the bottom. For navigation system, the drone was equipped with GPS, sonar system for altitudes higher than 2 to 4 meter, pressure altimeter for range altitude that sonar could not support accurately, temperature sensor, a three-axial magnetometer, and a three-axis gyroscope. Collected data were stored in internal storage to be downloaded after the ending the mission. The log file produced by this drone includes the recorded altitude, speed, position (latitude and longitude), and camera orientation (pitch and yaw) [29]. The Aeryon Scout drone was connected to the base station by using a radio modem with a range of 3 km.

In [30], a multihop emergency communication system was proposed to assist the miners and rescue team in emergency situations and improve mining productivity. The idea was to use a drone as a wireless communication framework, which was named SkyHelp, to monitor mining activity and support search and rescue operations in deep open-pit mines. A simulation was carried out by using MATLAB to assess the idea. Table 2 and Figure 1 summarize the characteristics of various types of drones used in surface mines. Table 3 also shows the applications of drones in surface mining.

### *CommerCialized Drones for Surface Mining Applications*

Besides the studies and tests carried out by researchers in the application of drones in mining industries, there are some commercialized drones that have been applied by companies for surface mining applications.

SenseFly (Switzerland, 2009): SneseFly is a commercial drone subsidiary of Parrot Group. This company produces both the drone's hardware and software for aerial data collection and analysis. The general specification of Snesefly products is shown in Table 4. Applications of SenseFly drone are inventory tracking (calculating stockpiles volumes, site surveying), traffic management (haul roads, loading floors and stockpile location optimization, blast planning), water management (accurate management of tailing dams, watersheds, drainage basins assessment and mapping the potential flow of water base on-site current topography), collaboration (improving operational planning, depletion accounting, monitoring environmental factors and making the decision on required maintenance work) [37,38].

Drone Deploy (USA, 2011): The company is a cloud software platform for commercial drones, which is especially compatible with DJI drones. This company provides software for aerial data analysis by drones for a variety of industries, including mining. The software is able to make 3D modeling of the area, contour line map, offline mine inspection, and stockpiles volume calculation. It has been claimed that Drone Deploy customers have mapped and analyzed more than 30 million acres in over 160 countries [39,40].

**Table 2.** Characterization of the used drone in surface mining [28–31,35].

| Type of Drone | Model | Goal | Wingspan (mm) | Length (mm) | Weight (g) | Endurance (min) | Payload (g) |
|---|---|---|---|---|---|---|---|
| Fixed-wing | Teklite | Characterization of blasting plumes | 900 | 575 | 900–950 | 45 | 200 |
| Fixed-wing | GoSurv | Characterization of blasting plumes | 850 | 350 | 900–1200 | 50 | >300 |
| Fixed-wing | Swamp Fox | Characterization of blasting plumes | 1800 | 1000 | 4500 | 40 | 1000 |
| Multirotor | Quadcopter | Characterization of blasting plumes | - | - | 2500 | 20 | 150 |
| Multirotor | Phantom 2 Vision+ | Topographic Survey | 35 cm | - | 1240 | 25 | - |
| Multirotor | Aeryon Scout | Measuring fracture orientations | 80×80×20 | - | 1300 | 25 | 400 |

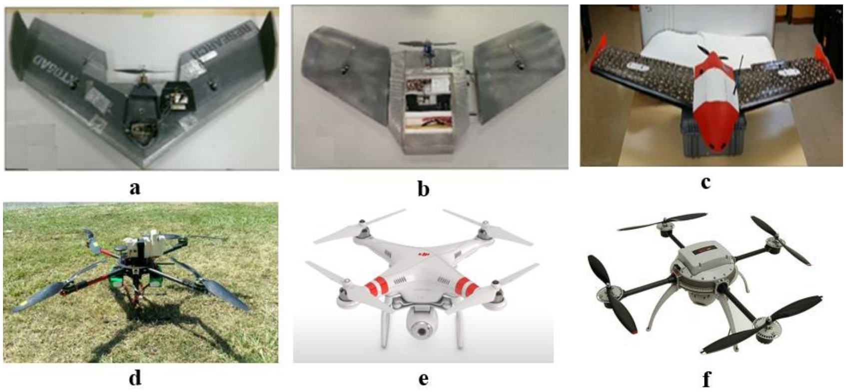

**Figure 1.** Views of the some utilized drones in surface mining (**a**) Teklite [35], (**b**) GoSurv [35], (**c**) Swamp Fox [35], (**d**) Quadcopter [35], (**e**) Phantom 2 Vision+ [36], (**f**) Aeryon Scout [29].

**Table 3.** Applications of drones in surface mining [18].

| Applications | Objectives |
|---|---|
| Safety and risk management | ■ Slump prediction, stability monitoring<br>■ Erosion detection<br>■ Asset location<br>■ Damage assessment<br>■ Incident monitoring<br>■ Livestock location |
| Daily routines and control | ■ Regular safety site survey<br>■ Management planning<br>■ Security and asset protection |
| Daily routines and control | ■ Regular safety site survey<br>■ Management planning<br>■ Security and asset protection |
| Monthly routines | ■ Mapping inaccessible areas<br>■ Boundary management |
| Strategic planning | ■ Pit and leach pad design<br>■ Road design<br>■ Slope assessment<br>■ Mineral exploration |
| Financial | ■ Stockpile volumetric calculation<br>■ Mobile and static resources calculation |
| Legal | ■ Boundary dispute data<br>■ Incident data capture |
| Environmental | ■ Water leakage detection<br>■ Vegetation encroachment<br>■ Tailings management and assessment |
| Infrastructure | ■ Track and access condition<br>■ Watershed, drainage, hydrology<br>■ Pipeline inspection<br>■ Leach pad construction, change, and erosion |

Kespry (USA, 2013): Kespry Company produces both drone's hardware and software for application in the mining industry. The drone properties of the Kespry Company are shown in Table 4. The services for the mining industry by Kespry Company include managing waste-rock and ore stockpile inventories, generating cut-and-fill reports for dragline operations, evaluating slope stability on active high-walls, reclamation planning, and verification of blasting pattern locations. The Kespry 2s drone delivers images with the 0.5 cm per pixel resolution. Because of the low flight time of multirotor, Kespry added the ability of field swappable battery on the drone. The obstacle avoidance of this drone is about (50 m) forward-facing by LiDAR sensor [41,42].

Propeller Aero (Australia, 2014): Propeller Aero produces software for aerial data analysis and uses customized DJI's Phantom 4 Pro (P4P) drone for aerial data collection. The properties of the DJI drones used by Propeller Aero are shown in Table 4. The Propeller Aero package provides a variety of services for the mining industry including: track the status of the mine, volume measurement tools for stockpile and pit volumes, plan blasting and extraction, monitor protected areas and avoid environmental fines, track progress against design, safety inspection, and keeping the haul road grades consistent. The Phantom 4 RTK is able to capture high-quality images with (2.1 cm) total vector distortion. The propeller drone shows the accuracy at or below (3 cm) by using multiple independent checkpoints over the site [43,44].

QuestUAV (United Kingdom, 2012): QuestUAV produces software for aerial data analysis and uses fixed-wing drones for aerial data collection. QuestUAV drone properties are shown in Table 4. These drones assist in a mining operation in a verity of disciplines (see Table 3). The drone has an accuracy of 3.2 cm over areas. Because of difficulty landing fixed-wing drones, a parachute is deployed by QuestUAV for a safe landing. In addition, launching is available by hand, designed air dock, or zip line. In addition, QuestUAV drones allow a series of payloads to be attached to the drone [45].

Skycatch (USA, 2013): Skycatch uses a multirotor drone for aerial data collection, a site base station which uses GPS and GNSS for accuracy in coordinates collection, and software for data management. Explore-1 drone is designed by Skycatch base on DJI Matrice M100 drone and manufactured by DJI Company. The general properties of Explore-1 drone are shown in Table 4. Komatsu Company tried to make the earthwork machine autonomous with Skycatch drone data. They used machine learning and deep learning to find patterns and improve data outputs [46,47].

Prioria (USA, 2003): Prioria was one of the first companies that has provided aerial data for the mining industry. This company produces both drone hardware for aerial data collection and software for data analysis. The general properties of Prioria products are shown in Table 4. These products perform aerial imagery, mapping, stockpile volume calculation, and inspections like pipeline and utility. The fixed-wing drones of this company are hand-launched and tube-launched. The precision of vertical volume calculation is 4 cm and for ground sampling distance it is 1.4 cm [48,49].

3D Robotics (USA, 2009): 3D Robotics produces software for aerial data analysis, which is compatible with Yuneec and DJI drones. The general specification of 3D Robotics drones is shown in Table 4. The available services by 3D Robotics aerial scan are geo-referenced maps and point clouds for mineral exploration, calculating the volumes of individual stockpiles, tracking inventory over time by calculating the volumes of individual stockpiles in every flight, improving site planning and coordination by pre- and postblast surveys, mitigating project risk and remote access to mine information by having near real-time drone and maps and data [50,51].

Trimble (USA, 1978): Trimble Company provides positioning technologies for a variety of industries, such as land survey, construction, agriculture, transportation, telecommunications, asset tracking, mapping, utilities, mobile resource management, and government. However, recently, this company applied drone technology for aerial data collection and analysis. The specifications of the multirotor drones of this company are shown in Table 4. The Trimble drones can provide boundary and topographic surveys, survey-grade mapping, power line modeling, field leveling, site, and route planning, progress monitoring, as-built surveys, resource mapping, disaster analyses, volume determinations, topographic contours, 3D surface models, and orthophotographs for mining industry [52,53].

Precision-hawk (USA, 2011): Precision-hawk offers software for aerial data analysis and uses other company's drones for aerial data collection. The specifics of DJI multirotor drones and birds-eye-view fixed-wing drone, which is used by Precision-hawk Company, are shown in Table 4. The software of this company provides the volume measurement tools for the pit, stockpile, and similar structure for the mining industry. In addition, outputs of the software could be useful in monitoring, planning, reports, safety and compliance, oversight, and reclamation. This company uses various kinds of sensors on the drones for aerial data collection. Sensors, such as thermal for tracking the relative temperature of the land and objects, multispectral for capturing near-infrared radiation and ultraviolet light which is invisible to human eyes, hyperspectral for identifying minerals, vegetation and other materials, LiDAR for collecting high-quality evaluation of natural and human-made objects, visual for capturing high-resolution aerial images, and video for live streaming and capturing video to on the ground devices can be integrated into the drones [54,55].

Pix4d (Switzerland, 2011): Pix4d uses images taken by drones, hand, or plane for data analysis by using the photogrammetry method. The software of this company is compatible with a variety of drone company products including DJI, Parrot, and 3DR. The services for the mining industry by Pix4d Software Company are as follows: (1) supporting blasting operations by locating boreholes, (2) monitoring blast sites without putting people in danger, (3) measuring stockpile volumes and excavated materials, (4) Pit mapping, and (5) toxic tailing dam mapping. It has been claimed that drone mapping could be performed in 20% of the traditional mapping method time, without disrupting traffic [56,57].

Microdrones (Germany, 2011): Microdrones produces both drones hardware and software for aerial data collection and analysis. The specification of the microdrone is shown in Table 4. The package of drones and software is able to map the deposit site, survey mine, explore minerals, monitor stockpile volume, track equipment, and make time-lapse photography. In addition, sensors like multispectral, thermal, LiDAR, and methane gas detection could be added to the drone for inspection. The drone positioning is carried out by GPS, and the postprocessing of the data method is aerial triangulation [56,57].

Delair (France, 2011): This company creates both software and drone hardware for aerial data analysis and collection. The package of software and drone of this company can provide stockpile volume, contour maps of the pit, finding potential hazards, detecting anomalies and doing the topography survey in the field without interrupting operation. Freeport-McMoRan, one of the largest American copper and gold mining company, used the DT18 Mapper drone package of Delair Company to do weekly topographical surveys for calculating the production capacity and creating digital surface models of the copper mine at Tenke Fungurume (TFM) in the Katanga Province of the Democratic Republic of Congo [58,59].

Table 4 and Figure 2 show the general specifications of commercial drones, including drone type, size, weight, endurance, payload, speed, wind speed resistance, and model name for use in the mining industry.

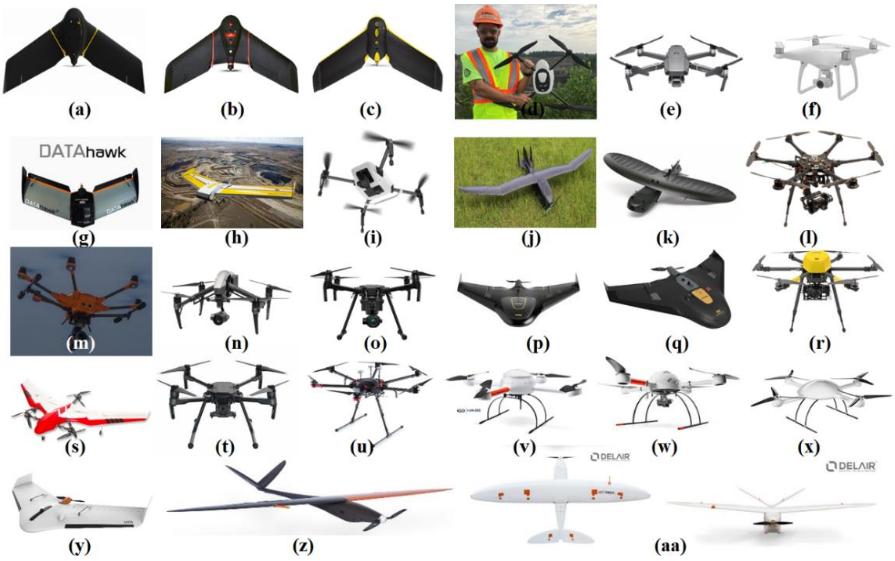

**Figure 2.** Views of the commercialized drones for surface mining applications; (**a**) eBee-X [38], (**b**) eBeeSQ [38], (**c**) eBee-Classic [38], (**d**) Kespry 2s [42], (**e**) DJI Mavic 2 [36], (**f**) DJI Phantom 4 Pro [36], (**g**) DATAhawk [60], (**h**) Q-200 Surveyor [60], (**i**) Explore-1 [47], (**j**) Leviathan [49], (**k**) Maveric [49], (**l**) Hex [49], (**m**) Yuneec 3DR H520-G [51], (**n**) DJI Inspire 2 [36], (**o**) DJI Matrice 200 [36], (**p**) UX5 HP – Trimble [53], (**q**) UX5-Trimble [53], (**r**) ZX5-Trimble [53], (**s**) FIREFLY6 PRO [55], (**t**) DJI MATRICE 210 [36], (**u**) MATRICE 600 PRO [36], (**v**) md4–200 [62], (**w**) md4–1000 [62], (**x**) md4–3000 [62], (**y**) UX11 [59], (**z**) DT18 HD [59], (**aa**) DT26X LiDAR [59].

**Table 4.** General specifications of commercial drones for use in the mining industry [38,40,42,44,47,49,51,53,55,57,59–61].

| Type of Drone | Model | Company | Wingspan (mm) | Weight (g) | Endurance (min) | Payload (g) | Speed (m/s) |
|---|---|---|---|---|---|---|---|
| Fixed-wing | eBee X | Sensefly | 1160 | 1400 | 90 | - | 11–30 |
| Fixed-wing | eBee SQ | Sensefly | 960 | 1100 | 55 | - | 11–30 |
| Fixed-wing | eBee Classic | Sensefly | 1100 | 690 | 50 | - | 11–25 |
| Quadcopter | Kespry 2s | Kespry | - | 2000 | 30 | - | - |
| Quadcopter | DJI Mavic 2 Pro | Kespry, 3D Robotics | 350 | 907 | 30 | - | 20 |
| Quadcopter | DJI Phantom 4 Pro | Propeller Aero, 3D Robotics | 350 | 1388 | 30 | - | 20 |
| Fixed-wing | Q-200 Surveyor | QuestUAV | 1950 | 4600 | 60 | 590 | - |
| Fixed-wing | datahawk | QuestUAV | 1164 | 2150 | 45 | - | 19 |
| Quadcopter | Explore-1 | Skycatch | 650 | 3600 | 17 | - | 17 |
| Fixed-wing | Leviathan | Prioria | 2590 | 5897 | 90 | 907 | - |
| Fixed-wing | Maveric | Prioria | 749 | 1179 | 45–90 | - | 13.5 |
| Hexacopter | Hex | Prioria | 800 | 6350 | 15 | - | 6.2 |
| Hexacopter | Yuneec 3DR | 3D Robotics | - | 1645 | 28 | - | 13.5 |
| Quadcopter | DJI M200 | Precision-hawk | 643 | 6140 | 13–24 | 1610 | 23 |
| Quadcopter | DJI Inspire 2 | 3D Robotics | 427 | 4250 | 32–27 | - | 26 |
| Hexacopter | Trimble ZX5 | Trimble | 850 | 5000 | 20 | 2300 | 9 |
| Fixed-wing | Trimble UX5 | Trimble | 1000 | 2500 | 50 | - | 22 |
| Fixed-wing | Trimble UX5 | Trimble (HP) | 1000 | 2900 | 35 | - | 24 |
| Fixed-wing | FIREFLY6 PRO | Precision-hawk | 1524 | 4500 | 50–59 | 700 | 15–18 |
| Quadcopter | DJI M210 | Precision-hawk | 643 | 4570 | 13–24 | 1570 | 24 |
| Hexacopter | MATRICE 600 | Precision-hawk | 1133 | 10000 | 18 | 5500 | 18 |
| Quadcopter | md4-200 | Microdrones | 540 | 800 | 25 | 250 | 8 |
| Quadcopter | md4-1000 | Microdrones | 1030 | 2650 | 45 | 1200 | 12 |
| Quadcopter | md4-3000 | Microdrones | 2052 | 6000 | 45 | 5000 | 20 |
| Fixed-wing | UX11 | Delair | 1100 | 1400 | 59 | - | 15 |
| Fixed-wing | DT18 HD | Delair | 1800 | 2000 | 120 | - | 17 |
| Fixed-wing | DT26X LiDAR | Delair | 3300 | 17000 | 110 | - | 17 |
| Quadcopter | ELIOS | Flyability | 400 | 700 | 10 | - | 6.5 |
| Quadcopter | ELIOS2 | Flyability | 400 | 550 | 10 | - | 4.68 |

## 4. Application of Arones in Underground Mines

Despite advancements in drone technology, the use of drones in underground mines has been limited [63]. This is because the application of drones in underground mines is challenging. Harsh underground environments pose many obstacles to flying drones. Confined space, reduced visibility, air velocity, dust concentration, and lack of wireless communication system make it a difficult task for an operator to fly a drone in underground working areas. Furthermore, access to unreachable and dangerous locations in underground mines is practically impossible for a drone operator [63].

Drones in underground mines have numerous potential applications in health and safety. These applications include surface roughness mapping, rock mass stability analysis, ventilation modeling, hazardous gas detection, and leakage monitoring [32,63–68].

### *4.1. Geotechnical Characterization of Underground Mines*

Rock mass data collections in underground opening usually require the inspector(s) to survey the rock mass physically. The presence of the personnel in unsupported areas such as open stope and newly blasted working faces endangers the safety of the personnel [69]. Drones are tools that are more suitable to be used in underground mines during the monitoring of unreachable areas. Small size and maneuverability of drones allow them to access hard-to-reach areas in underground mines without endangering the life of the miners. Imagery techniques such as photogrammetry and FLIR (forward-looking infrared) allow characterizing rock masses. Photogrammetry can provide data for generating geological models and structural data for kinematic and numerical analyses. In addition, FLIR imagery can be used to recognize areas of loose rock, which normally remain unnoticed until it becomes a hazard [69].

### *4.2. Rock Size Distribution Analysis in Underground Mines*

The majority of underground hard rock mines use drilling and blasting methods for rock extraction. Assessment of rock size distribution after blasting is an important measurement for next production phases (i.e., loading and hauling) [70,71]. There are some methods for rock size distribution analysis, including visual observation by an expert, sieve analysis, and image processing. Image analysis methods are fast and relatively accurate for rock fragmentation measurements [71,72].

### *4.3. Gas Detection in Underground Coal Mines*

A set of sensors to continuously measure atmospheric parameters and gas concentration will enable a drone to be used for hazardous gas detection in underground mines. Lucila and Masami used an unmanned aerial vehicle for gas detection in underground coal mines [32]. In this research, a gas sensor installed on a drone utilized as a safe and reliable surface measurement of coal fire gases for assessing characteristics of underground coal fires. DJI S1000 Octocopter drone (specification in Table 5) was used for carrying gas sensors. With the combination of this drone and sensor, they could achieve 10 to 15 minutes flight time [32].

### *4.4. Mine Rescue Mission in Underground Mines*

Hoffman and McAllister, in 2018, proposed using an Unmanned Ground Vehicle (UGV) combined with a drone to find the location of trapped workers [73]. The UGV scans the tunnel map during the drive to the destination and provides a variety of information about the conditions of the tunnel. The scenario is that the UGV, which would carry a drone onboard, drives to the location. Then, the drone would launch at the appropriate location to assess the collapsed area and to find any gap through the pile of rock or soil. The role of UGV is to carry the drone, scan the tunnel with a LiDAR sensor, and dock the drone when the mission is completed or drone battery needs recharging [73]. They used a Flame Wheel D JI's F450 drone as a joint with UGV to carry sensors to the corners of the space that UGV does not access to them. Quadcopter F450 is a multirotor drone designed by the DJI Company.

Its takeoff weight is 1600 grams, which is mentioned as a low payload for this kind of mission [73]. Table 5 summarizes the characteristics of various types of drones in underground mines. Figure 3 shows the drones that have been used in underground mines.

**Table 5.** Characterization of the used drone in underground mining.

| Type of Drone | Model | Goal | Wingspan (mm) | Weight (g) | Endurance (min) | Payload (g) | Speed (m/s) |
|---|---|---|---|---|---|---|---|
| Helium gas balloon | Zeppelin | Monitoring inaccessible areas in an underground mine [64] | 1200 | - | - | - | - |
| Octocopter | DJI S1000 | Gas detection of underground coal fire [32] | 1045 | 4.2 | 15 | 1800~6800 | - |
| Quadcopter | DJI M210 | Reduce personnel exposure to unsafe conditions of underground mines [65] | 643 | 4570 | 13–24 | 1570 | 12 |
| Quadcopter | MATRICE 100 | Geotechnical data collection [66] | 650 | 2431 | 23 | 1169 | 5 |
| Quadcopter | D JI's F450 | Underground void mapping [67] | 450 | - | - |  | - |
| Quadcopter | D JI's F450 | Underground mine rescue | 450 | 800–1600 | 33 |  | - |
| Quadcopter | ELIOS | Supporting backfilling operations by monitoring shadow areas, identifying ground conditions in open stopes, and inspecting conveyor belts without interrupting operation [68] | 400 | 700 | 10 | - | 6.5 |
| Quadcopter | ELIOS2 | Same as ELIOS | 400 | 550 | 10 | - | 4.68 |

(a) (b) (c) (d)

**Figure 3.** Commonly used drones in underground mines (**a**) Zeppelin [64], (**b**) DJI M210 [65], (**c**) ELIOS 1 [68], (**d**) ELIOS 2 [68].

### *4.5. Common Sensing Methods for Drones in Underground Mining*

Many sensing technologies are used for underground mining applications, including the stereo camera, ultrasonic sensors, dual redundant IMUs, and infrared sensors used by DJI [36,74]. Ultrasonic sensors are low-cost sensors for obstacle detection that have been tested by several studies. Other kinds of obstacle detector sensors that are repeatedly used by researchers include infrared sensors, stereo cameras, and laser range finders (LRFs) [75–80].

### *4.6. Challenges in Using Drones in Underground Mines*

The nature of underground mine environments and other obstacles (e.g., surrounding walls, loose bolt, cables, and equipment) require the drone to be collision tolerant. Ideally, the drone should be able to detect and avoid obstacles during its flight in the indoor environment. Since the underground mine sites are constantly expanding, the coverage area of communication increases as the operation continues [81], which creates a challenge for a drone to cover the entire mine during regular working operation as well as in emergencies [82].

Due to the existence of obstacles in underground mines, the main problem of using drones is signal propagation. There is a need for a radio signal connection between the drone and the remote controller in order to fly the drone. The environment continually absorbs the signal's energy. Therefore, if a drone flies far in the underground environment, it will lose its signal, and consequently, it is not able to return to the deployment point [83]. To solve this challenge, a transmission system can be integrated into the drone. This is efficient enough to allow the drone to fly far away into the down curved, underground passages and tunnels without loss of signal coverage. It also sends a constant video stream of what the drone camera is recording [83].

The battery life limits the flying time of drones. In many circumstances, battery replacement is required to extend the flying time. The weather situation in underground mines also can affect battery life and safety [84,85]. There are drones that employ hybrid power systems (i.e., batteries plus combustion engine) to perform longer-duration missions [86,87].

Additionally, humidity or water leakage damage the electronic components of the drones and interfere with the communication between the drone and its controller [86,88]. The visibility of people and objects in real-time is important to avoid accidents. However, there are many circumstances in which visibility is not sufficient to proceed with a mission using a drone [63,89].

## 5. Application of Drone Technology in Abandoned Mines

The website of the Bureau of Land Management reports as of 2016, in the United States, tens of thousands of abandoned mines have been registered [90]. The website also estimates that approximately 500,000 abandoned mines exist in the nation [90]. Abandoned mine lands (AMLs) pose environmental, health, and safety threats to humans [90]. An example is the miners of Somerset, Pennsylvania, who accidentally died by breaching an abandoned flooded mine. The miners were not aware of the existence of the nearby abandoned mine [91,92]. Another example is the existence of "bord and pillar" underground mines in Newcastle (NSW) and Ipswich (QLD) in Australia. The mines are now abandoned and located beneath residential areas, which elevates the risk of ground subsidence [93]. Similarly, subsidence is being monitored for the abandoned gold mines in Nova Scotia and Ontario, Canada and coal mines in Illinois and Ohio, USA [94].

Moreover, when a coal mine is abandoned, the methane emission is reduced but does not completely stop. Abandoned mines can liberate methane at a near-steady rate for an extended period of time. Flooding of the mines can inhibit gas emissions and buildups in the empty spaces; this would also help to mitigate the danger level of working in active mines nearby [95,96]. Therefore, monitoring and mapping abandoned mines are important to decrease the risk of environmental hazards. However, monitoring of such vast areas with the traditional, labor-intensive, expensive monitoring methods is challenging. Drone technology, as a financially efficient approach, can be an alternative solution. Tables 6 and 7 summarize the applied drone's missions in abandoned mines.

**Table 6.** Applications of drone technology in abandoned mines missions.

| Mine Type | Application | Description |
|---|---|---|
| Surface Mines | Surveying photogrammetry and hazardous subsidence mapping | - Creating a subsidence inventory map demonstrating the locations and details of past subsidence occurrence [18,97–99]. |
| | Photogrammetry and filling material calculation | - Creating a high-quality 3D digital elevation model (DEM) to calculate the amount of required soil for the recultivation of a closed mine [100,101]. |
| | Anthropogenic formations of invasive plants on Abandoned Mine Lands | - Creating a map and determining accurate dimensions and volumes of anthropogenic landscape forms, such as landfills [102].<br>- Mapping of places where some invasive plants exist [102]. |
| | Rehabilitation | - Creating a 3D train model of mine lake in order to rehabilitate the abandoned mine [103,104]. |

**Table 6.** *Cont.*

| Mine Type | Application | Description |
|---|---|---|
| Underground Mines | Pillar mapping | - Collecting data, communicating, and mapping pillars in abandoned underground mines when there is a risk of deploying a crew [105–107]. |
| | Detection of gas storage | - Creating a 3D virtual mine map from 3D point cloud information of optical sensors to calculate the volume capacity for gas storage in abandoned mines [95,96]. |
| | Monitoring acid mine drainage | - Investigation and monitoring of acid mine drainage from abandoned mines and tailings to the water stream [108]. |
| | Mine shaft investigation | - Combination of the GPS data with the digital photographs taken by the drone to create orthorectified photography maps [18,109–111]. |

**Table 7.** Characterization of the drones used in abandoned mines.

| Type of Drone. | Model | Goal | Where | Wingspan (mm) | Weight (g) | Endurance (min) |
|---|---|---|---|---|---|---|
| Multirotor | Phantom 2 Vision+ | Surveying photogrammetry | Open-pit limestone mine in Korea | 3500 | 1240 | 25 |
| Fixed-wing | - | Photogrammetry | Open-pit mine | 1000–3000 | 2000–5000 | - |
| Fixed-wing | AeroVironment RQ-11 Raven | Rehabilitation | Coal mine | 1372 | 1906 | 60–90 |
| Fixed-wing | SenseFly swingletCAM | Mine shaft investigation | Coal mine in UK | 116 | 1100–1400 | - |
| Multirotor | Honeywell RQ-16 T-Hawk | Rehabilitation | Coal mine | - | 8390 | 40 |

## 6. Application of Drones in Search and Rescue Operations

Most of the mines are in a remote area where common, reliable communication systems may not be available. Drones provide rapid solutions in support of communications coverage of rescue operations [112,113]. Drones can provide disaster warnings and assist with accelerating rescue and recovery operations when the communications networks are not serving anymore. Drones also have the capability to carry medical supplies to hard-to-reach areas. In certain circumstances (e.g., poisonous gas infiltration and searching for missing persons), drones can support the role of accelerating these operations [114]. Table 8 shows a few examples of the application of drones in mine rescue missions.

**Table 8.** Examples of mining industry safety and rescue drone applications.

| Company | Mine site | Application |
|---|---|---|
| Hexagon | Coal mine | - The thermal image camera of the drone detects heat arising from the facilities in the dressing plant, such as the conveyor belt system, to prepare for the problems due to the overheating of the facilities. It can also quickly detect the self-ignition point of the coal in the coal mine to monitor accidents [115]. |
| Tir3D | Abandoned mineshaft in an exhausted mine | - The drone technology helps to prevent the environmental disruption caused due to mining by effectively investigating the location of the mineshaft of an exhausted mine [116]. |

## 7. Commonly Used Sensors on Mining Drones

Fast technological advancements in both passive and active sensors have empowered the capability of drones in various types of missions [117,118]. Sensors on drones facilitate image capturing at centimeter and spatial resolution and time-dependent resolution at temporal [117,119–122]. The sensors on a drone depend on drone size and the mission. However, depending on the goal of the aerial investigation and the lighting condition, various kinds of sensors need to be attached to the drone.

These include the RGB sensors, ultrasonic sensors, Infrared Sensors (IR), stereo camera, laser range finders (LRFs), Ultra-Wideband Radar (UWB), and hyperspectral sensors. Figure 4 shows examples of commonly used sensors in drones in the mining industry.

### *7.1. Infrared Sensors (IR)*

Infrared Sensors (IR) are a kind of low-cost obstacle detector sensor. Infrared radiation can be either detected or emitted by IR. Generally, all materials above absolute zero emit waves in the infrared spectrum. Infrared sensors, considered as heat sensors, can detect the energy radiation of objects. Despite the limited resolution, infrared sensors have the ability to detect human [75,80,132]. On the one hand, it has the advantage of sensing through fog, smoke, day, and night. However, on the other hand, it can be distorted by flame and any other high-temperature sources. Moreover, it does not work well through thick dust [75,132].

### *7.2. Ultrasonic Sensors (US)*

Being inexpensive and uncomplicated make ultrasonic sensors viable for various applications. These sensors detect the obstacles by radiating high-frequency sound waves and collecting reflected waves. The distance to the obstacles can be determined by considering the time-of-flight technique. An ultrasonic sensor is the only common sensor in the drone technology that is not based on electromagnetic waves (EM). The disadvantage of the ultrasonic sensor is detecting sound-absorbing materials, like cloth, for example. Besides, it has a shorter range than another type of sensors [75,76,80].

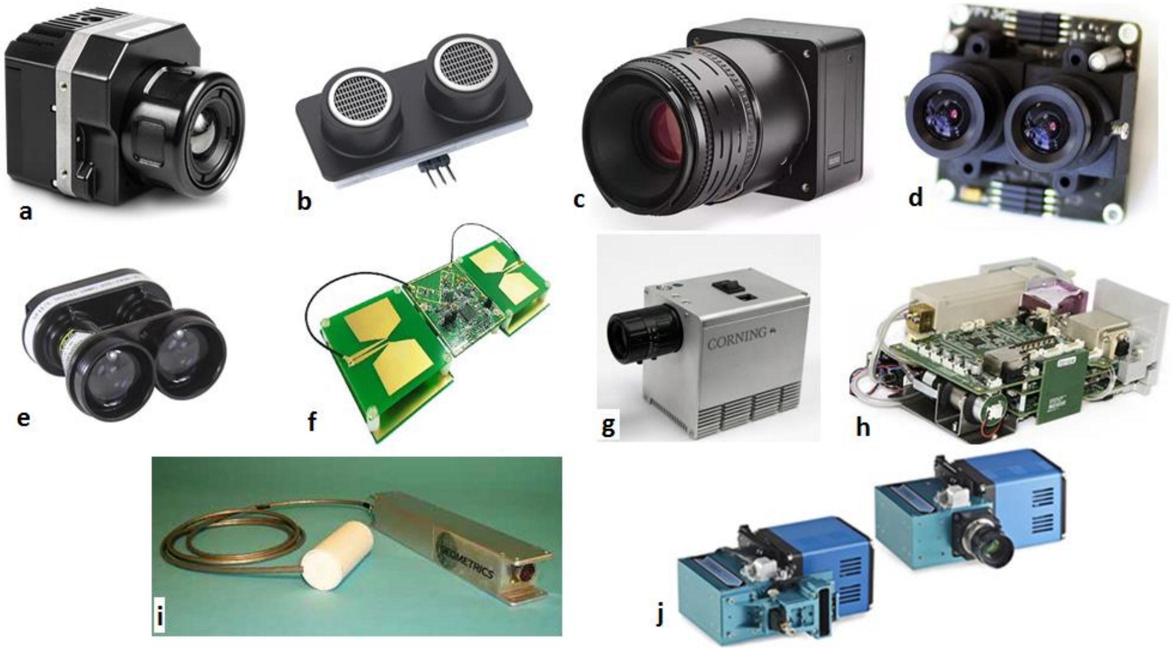

**Figure 4.** Examples of commonly used sensors on the mining drones: (**a**) infrared sensor [123], (**b**) ultrasonic sensor [124], (**c**) RGB camera [125], (**d**) stereo cameras [126], (**e**) laser range finders [126], (**f**) ultra-wideband radar (UWB) [127], (**g**) hyperspectral sensors [128], (**h**) magnetic sensors [129], (**i**) gas detector [130], (**j**) visible and near-infrared spectral range (VNIR) [131].

### *7.3. Red-Green-Blue (RGB) Sensors*

RGB camera can be used in surveying and mapping, stockpile volume calculation, road traffic monitoring, security monitoring, inspection, etc. RGB camera is a sensing system that takes RGB (Red Green Blue) images, including a per-pixel depth report. RGB cameras work with one of two active stereos [133,134] or time-of-flight sensing to create depth evaluation at a huge number of pixels [133].

Camera selection needs to be done carefully, considering the drone's fuel consumption. Generally, a compact camera is preferred for fixed-wing drones because heavy devices cannot be carried [18].

### *7.4. Stereo Cameras*

The stereo camera is a kind of camera that is equipped with two or more lenses to create 3D images, similar to the human visual system. Stereo cameras are able to develop three-dimensional images by their separate image sensors. High resolution and accuracy in a clean environment are the advantages of stereo cameras. However, it has poor performance in smoke, fog, or dust, because the light waves are distorted in such conditions [80].

### *7.5. Laser Range Finders (LRFs)*

Laser range finders (LRFs) are expensive sensors commonly used for obstacle detection in drone technology. In LRFs, a laser beam is radiated to an obstacle, and by receiving a reflected wave and considering time-of-flight, the distance to an object can be measured. As LRFs use optical wavelengths of light, it is not suitable for conditions like fog, smoke, dust, or similar adverse conditions [80].

### *7.6. Ultra-Wideband Radar (UWB)*

Obstacles detection by Ultra-Wideband Radar (UWB) is carried out by emitting electromagnetic waves in the radio spectrum. Similar to US and LRFs, the distance to the target can be measured by taking into account the reflected wave and times-of-flight. However, radar's radio waves have a longer wavelength than visible light and infrared. Therefore, radio waves have better penetration than visible light in the dust, fog, smoke, and other adverse conditions [80,135].

Ultra-Wideband Radar (UWB) has some features that make it suitable for mining drones. First, it has a more precise and higher image resolution compared to the ultrasonic sensors in harsh environmental conditions like fog, smoke, dust, rain, snow, gas, and aerosols [77,80,132]. Second, UWB uses low energy that is generally less than 1 Watt. This means drone battery power can be saved for other utilities [80,136]. Third, regarding low spectral density, UWB has minimum interference with other wireless uses like flight controller and telemetry link [80,136]. Fourth, UWB can detect different characteristics like walls, edges, and corners. Finally, it can identify the three-dimensional coordinates of the nearest object [137].

### *7.7. Hyperspectral Sensors*

Recently, lightweight hyperspectral imaging (HSI) sensors are being developed for use on drones [138–140]. Most of the multispectral imagers (Landsat, SPOT, and AVHRR) detect reflectance of Earth's surface material at several wide wavelength bands which are separated by spectral segments. In other words, hyperspectral sensors assess reflected radiation as a series of narrow and contiguous wavelength bands. Typically, bands are measured at 10 to 20 nm intervals by hyperspectral sensors [141]. These sensors can provide information that is not accessible by traditional methods. In general, this kind of sensor is widely used in geology, mineral mapping, and exploration [140,142–145].

### *7.8. Magnetic Sensors*

The magnetic sensors produce an accurate measurement of the magnetic field. Moreover, magnetic sensors assess disturbances and changes in the magnetic field include flux, strength, and direction [146]. The normal weight of a Cesium magnetometer, such as the Scintrex CS-3Sl, is about 0.82 kg. It should be noted that for deriving three-dimensional magnetic field gradients, there is a need for four magnetometers. This means 3.28 kg would be the total weight of the Magnetic sensors. This kind of sensor could be useful in mineral exploration [147].

### *7.9. Visible and Near-Infrared Spectral Range (VNIR*

VNIR sensors of the electromagnetic spectrum are usually preferred to be installed on drones due to their small size and low weight. The wavelength at intervals of about 400 and 1400 nanometers (nm) is called the visible and near-infrared (VNIR) portion of the electromagnetic spectrum [148]. This range consists of the complete visible spectrum with an adjacent part of the infrared spectrum up to the water absorption band at intervals 1400 and 1500 nm [149]. In addition, there are some definitions that cover the short-wavelength infrared band from 1400 nm up to the water absorption band at 2500 nm [149]. These sensors could be used for surface moisture of open pits [150], tailing dams, underground spaces wall, and surfaces. In addition, each particulate mineral has a special signature in VNIR spectra [151], which is an advantage in mineral exploration by drones equipped with VNIR sensor.

### *7.10. Air Quality Sensors*

On top of the aforementioned sensors, specific sensors (e.g., air quality, gas sensing, dust monitoring, etc.) can be installed on a drone for a particular mission. Table 9 shows examples of sensors that are used for air quality testing and gas detection. Typically, the air quality sensors are based on optical, ultrasound, and electrochemical sensing elements [35]. These sensors could be handheld personally, installed on the vehicle, or from ground-based network systems. Many of these sensors can be installed on a drone depending on the type of contamination, release time, and measurement requirements. For example, rotary-wings drones have been used to sense water vapor and $CO_2$, $CH_4$ [152], ethanol and $CH_4$ [96,153], $NO_2$ and $NH_3$ [154,155], $CO_2$ [154,156], $SO_2$ [157]. Lega et al. visualized air pollutants in 3D and real-time by using a multirotor drone [158]. Moreover, different types of this platform were used to identify sewage discharges along with Italy coastline by sensing gases include CO, $C_6H_6$, $NO_2$, $O_3$, $SO_2$, NOX, and PM10, besides thermal IR images [154,158,159]. At present, fixed-wing drones can stream real-time monitoring as well as supplying indexed-linked samples [154,158].

**Table 9.** Examples of sensors used in mining, oil, and gas industries for sensing gas and dust [35].

| Instrument | Description | Gases/Particles | Characteristics |
|---|---|---|---|
| **Handheld** | | | |
| Dräger X-am 5600 | Close-packed instrument for the measurement of up to 6 gases; follow standard IP67; IR sensor for $CO_2$ and electrochemical for other gases. | $O_2$, $Cl_2$, CO, $CO_2$, $H_2$, $H_2S$, HCN, $NH_3$, NO, $NO_2$, $PH_3$, $SO_2$, $O_3$, Amine, Odorant, $COCl_2$ and organic vapors. | Dimensions:<br>4.7 × 13.0 × 4.4 cm<br>Weight: 250 g |
| **Installed in ground vehicles** | | | |
| Picarro Surveyor | Cavity ring-down spectroscopy (CRDS) technology, sensitivity down to parts-per-billion (ppb); survey gas at traffic speeds and map results in real-time; real-time analysis to distinguish natural gas and other biogenic sources. | $CO_2$, CO, $CH_4$, and water vapor | Dimensions: Analyzer 43.2 × 17.8 × 44.6 cm; external pump 19 × 10.2 × 28.0 cm<br>Weight: 24 kg + vehicle<br>Power: 100–240 VAC |
| Tapered Element Oscillating Microbalance (TEOM) | Continuous particle monitoring. The tapered element consists of a filter cartridge installed on the tip of a hollow glass tube. Additional weight from particles that collect on the filter changes the frequency at which the tube oscillates. | Total suspended particles (TSP), PM10, PM2.5 | Dimensions:<br>43.2 × 48.3 × 127.0 cm)<br>Weight: 34 kg<br>Power: 100–240 VAC |
| **Networks** | | | |
| AQMesh | Wireless monitor; high sensitivity (levels to ppb); designed to work through a network of arrayed monitors. | NO, $NO_2$, $O_3$, CO, $SO_2$, humidity and atmospheric pressure. | Dimensions:<br>17.0 × 18.0 × 14.0 cm<br>Weight: <2 kg<br>Power: LiPo batteries |
| **Airborne** | | | |
| Yellow scan | LIDAR technology with a total weight of 2.2 kg;<br>80,000 shots/s; resolution of 4 cm;<br>class 1 laser at 905 nm. | Dust and aerosols | Dimensions:<br>17.2 × 20.6 × 4.7 cm<br>Weight: 2.2 kg<br>Power: 20 W |

## 8. Discussion

### *8.1. Challenges in Using Drones in the Mining Industry*

In surface mines, weather conditions present a challenge by inducing deviations in drone's predesignated paths compared to underground mines. In some cases, weather conditions can be damaging to the drones, leading to failure in their missions [113,160]. In the mining industry, as well as other industries, energy consumption during a mission can impose many challenges. Normally, drones run on battery and consume the energy for hovering, wireless connection, data, and image processing. Due to the power restrictions as such, a decision needs to be made on whether data and image analysis should be performed onboard in real-time or offline to reduce energy consumption [113,161,162].

In underground mines, confined space, heat and humidity, dusty air and poor lighting conditions are the main issues that mineworkers generally face. Some concepts have been proposed for using drones in underground mines, but usually are applying manual techniques for control and navigation. At a minimum, the designed drone should be capable of fully autonomous navigation in a completely GPS-denied environment and fly in an environment with no lighting other than that provided by the drone. Nature of underground mine environments and other constraints (e.g., surrounding walls, loose bolt, cables, and equipment) require the drone to be collision tolerant. Ideally, the drone should be able to detect and avoid obstacles during its flight in the indoor environment. The drone should also tolerate harsh underground mine environments and fly in heavy dust and smoke. Therefore, the drone should be waterproof, dustproof, shockproof, and should resist pressure, temperature, and humidity changes throughout the mine site. For underground coal mine applications, due to the presence of methane and potential explosion/fire hazards, the battery and the electronic sensors must be insulated. Adding to the above-mentioned requirements, the drone should provide other features, including low power consumption and human body detection.

### *8.2. Suitable Drone Configuration for Underground Mining Applications*

As mentioned above, there are some challenges in using drones in underground environments. To this end, there is a need to design an optimized microdrone that can address all of these challenges. The first step in designing a drone is configuration development. Considering an underground mine environment, a drone with hovering capability can be designed. One of the types of microdrones is multirotors, which allow them to fly in confined spaces. These drones, which can hover and have high maneuverability due to rotary blades or propeller-based systems, are called rotary-wing drones. Unlike the fixed-wing models, these drones can fly in every direction, horizontally, vertically, and also can hover in a fixed position. Rotary wing drones, similar to helicopters, generate lift from the constant rotation of the rotor blades. In this type of drone, several blades may be used. Thus, nowadays, researchers designed and fabricated different types of drones ranging from one to twelve motors. These characteristics make them the perfect drones for surveying hard-to-reach areas, such as pipelines, bridges, mines, etc.

Having drones that are confined in boxes is necessary for situations in which the surrounding environments are unknown. To this end, there is a need to design structures to keep the drones safe. Different structural configurations have been proposed in order to be able to use these drones in underground mines, in the wake of natural disasters, and in the presence of people (Figures 5 and 6). The structure around the drones allows safety for the drone, along with allowing the drone to have a rolling feature. The drones, with their encasing optimized structure, have the ability to fly through confined spaces like mines and have the capability to roll on the ground and walls of the mines if needed. Considering the environment, a drone with a flexible spherical structure can be designed, which will be able to fly in high temperatures and dusty air in the mines. In the following, different types of the encased drones are discussed. Table 10 shows examples of encased drones for industrial and research applications.

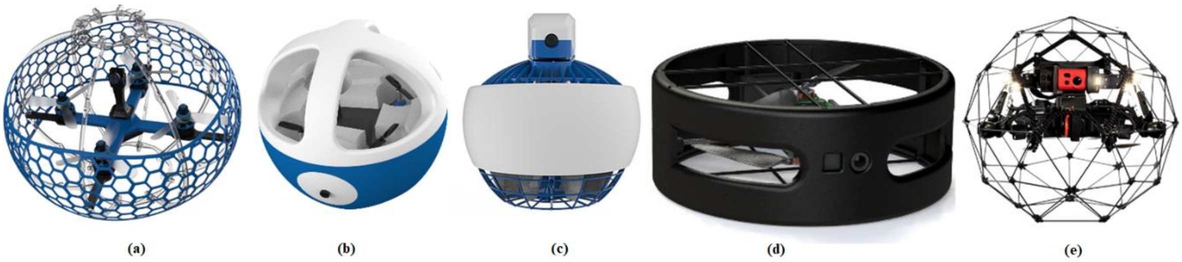

**Figure 5.** View of encased drones, (**a**) Fleye Racer [163], (**b**)Fleye Helmet [163], (**c**) Fleye Ducted [163], (**d**) Flybotix drone [164], and (**e**) Elios 2 [68].

**Table 10.** The characteristics of industrial encased drones [68,164,165].

| Type | Model | Goal | Company | Diameter (mm) | Weight (g) | Speed (m/s) |
|---|---|---|---|---|---|---|
| Single rotor | Fleye Racer | Learn how to fly a drone | Fleye | 110 | 235 | 27 |
| Four propeller | Fleye Helmet | Learn how to fly a drone | Fleye | 210 | 210 | 11 |
| Single rotor | Fleye Duct | Learn how to fly a drone | Fleye | 110 | 400 | 4 |
| Dual rotor | FLYBOTIX | Industrial Inspection | Flybotix | 300 | - | - |
| Quadcopter | Elios 2 | Industrial inspection | Flyability | 400 | 1450 | 1.5 |
| Single Rotor | UFRO | Search and rescue | Oklahoma State University | 560 | 950 | - |
| Encased single-rotor | Glimball | Flying multiple collisions environment | Laboratory of Intelligent Systems-Switzerland | - | 385 | 1.5 |
| Encased Multirotor | PRSS UAV | Indoor inspection after the disaster | Tohoku University Japan | 894 | 1956 | 2.5 |
| Encased single-rotor | Spherical drone | Indoor operations | Cranfield University | 226 (inner) | 590 | - |
| Encased Multirotor | Sphere | flying spherical display surface | Research Labs, NTT DOCOMO | 880 | 4500 | - |

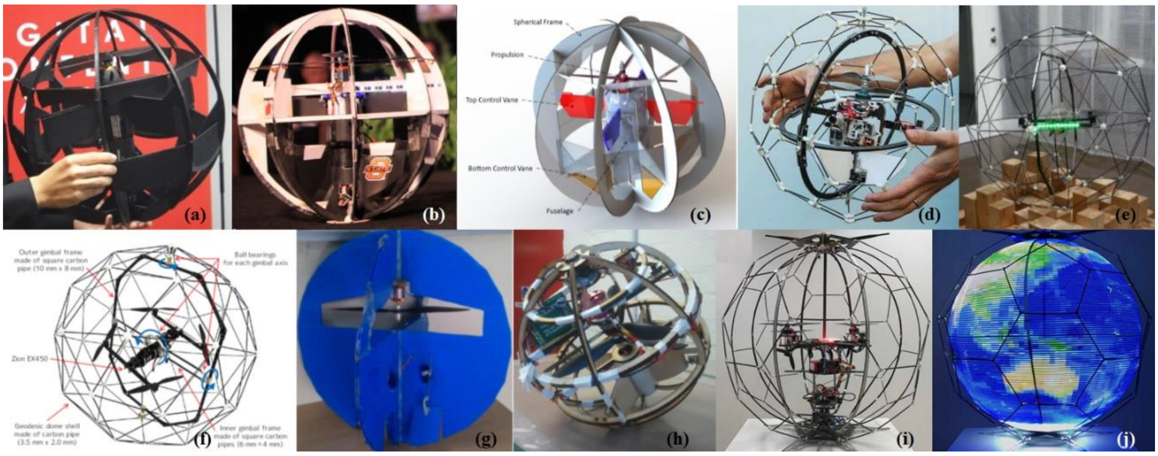

**Figure 6.** View of encased drones, (**a**) Spherical Drone [166], (**b**, **c**) UFRO [167], (**d**) Glimball [168], (**e**, **f**) PRSS UAV [169], (**g**) Simha et al.'s Drone [170], (**h**) Spherical Drone [171], and (**i**,**j**) isphere [172].

## 9. Conclusions

In this paper, recent studies and developed commercial drones and services in the mining industry were discussed. In addition, the drone applications in the mining industry for search and rescue missions were discussed. Besides, common remote sensing tools that have been mounted on drones in the mining industry were reviewed. Drone technology is a common tool in surface mining. It is efficient and low cost compared to the traditional monitoring methods. Drones in surface mining have a variety of applications, such as ore control, rock discontinuities mapping, 3D mapping of the mine environment, blasting management, postblast rock fragmentation measurements, and tailing stability monitoring, to name a few. Fixed-wing and rotary-wings drones are the most commonly used drones in the mining industry, including both research and commercial applications.

Despite significant advancement in drone technology, the applications of drones in underground mines are still limited. This is due to challenges like GPS-denied environments, lack of wireless signal, confined spaces, the concentration of dust and gases, and generally harsh environments. The possible solution for the use of drones in underground mining was suggested. Encased drones can be a solution to the environmental obstacles in underground mine environments.

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