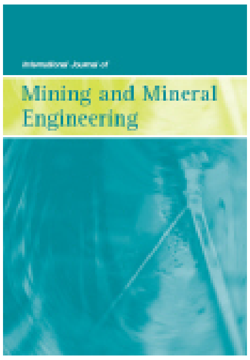

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Towards application of positioning systems in the mining industry

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Abstract: Positioning and communication systems hold intriguing potentials in the context of the mining industry. The need for safety and environmental precautions in mining has grown clearer for governments and scientists across the world. This is in light of complex and hazardous mining situations which can be tackled by the advancement of science and technology. This paper discusses how positioning systems have enhanced mining operations' safety, productivity and environmental sustainability. The drawbacks of positioning systems in the mining industry are established and analysed by examining the influence this technology has had on the different operations in the mineral industry. The possibility of their utility for precise localisation in situations when no other techniques exist has been carefully evaluated for recent uses of these technologies in the mineral industry. Future study must address a few significant issues and gaps that have been identified.

Keywords: automated-tracking; communication technologies; localisation; positioning systems; real-time navigation; radio-frequency identification; RFID.

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1 Introduction

Mining is the most important sector in the chain of supply chain for materials used in manufacturing, technology development, and construction. The discovery and exploitation of minerals, including metals, non-metals, aggregates, coal, and strategic elements like rare earth elements, are essential to modern life (Dayo-Olupona et al., 2023; Said et al., 2023). The need for resource exploitation is made more urgent by population growth. The estimation of ore reserves is uncertain, in situ rock's nature is unknown, the operation requires energy, commodity prices are volatile, working conditions are hazardous to the health and safety of miners, and environmental concerns make it difficult to extract minerals (Carvalho, 2017). Remote automated machinery, real-time data monitoring, remote sensing, three-dimensional ore resource simulation and extremely efficient excavators are just a few of the technological advancements that have helped the mining sector overcome these difficulties (Dayo-Olupona et al., 2020).

A crucial enabling technology for traffic management, automation, and safety in the presence of several operational vehicles in the mining industry is the capacity to ascertain the position and orientation of vehicles in real-time. Due to the numerous applications and related services, it offers, such as resource tracking, emergency response planning, employee tracking and machine tracking, indoor positioning has grown in prominence over the past few decades (Zhou et al., 2020; Zare et al., 2021). Massive amounts of rocks must be removed from the ground and handled during underground mining operations, which cannot be done without achieving occupational health and safety. With the advancement of technology, innovative spaces like smart offices and smart homes are now present everywhere (Cavur and Demir, 2022). As a result, it is now viable to create smart mining environments with technical advancements, including communication devices.

For companies looking to boost productivity and utilise fewer resources, the location of objects in an environment is becoming more and more crucial. The real-time location system (RTLS) solutions that are now offered rely on wireless fidelity (Wi-Fi), radio-frequency identification (RFID) or ultra-wideband (UWB) technology to determine a location. These systems make it possible to locate and identify objects in both confined and open environments in real-time (Cavur and Demir, 2022; Ziegler et al., 2023). Numerous operational risks to people might arise in the underground mining environment. These include being near powerful machine, roof falls, hydraulic and electrical systems and exposed to dust and possibly explosive mining gases (Zare et al., 2021; Ziegler et al., 2023). For decades, miners have been forced to labour in this dangerous environment to physically control the equipment at close range in the absence of technological automation, ensuring the effective operation of the mining process. The industry required solutions to these issues after realising that they were growingly unsatisfactory and unsustainable in the long run (Thrybom et al., 2015).

Indoor location, in particular RFID-based systems, can assist in achieving that goal by tracking each employee and equipment in a deep mine in real-time (Ni et al., 2004; Medina et al., 2013). The ability to simultaneously monitor mining processes, reduce occupational risks, act swiftly to prevent fatalities in the case of an accident, and incorporate additional monitoring systems, including pressure detection and gas detection, into deep mines will be made possible by this. Because effective tracking technology deployment can reduce operating costs in surface mines, it will also reduce operating costs in underground mines (Zare et al., 2021; Cavur and Demir, 2022).

The bulk of positioning systems in underground mines nowadays are access and entry systems, which are used to ascertain people entering and leaving the mine at some crucial entrance and departure locations (Zare et al., 2021). These systems keep track of each person inside the mine, as well as their general location or depth, if applicable. Prior to each blast, all personnel must be in a secure area or outside the underground mine (Thrybom et al., 2015). According to Li et al. (2018a), tracking underground is vital for the efficiency of the mine and the safety of the mining personnel. Casualties could be excessive if the safety requirements to prevent mining accidents are not even met. Information that is accurate and current can help save the lives of miners (Firoozabadi et al., 2019). Therefore, any viable system that gives decision-makers access to real-time information regarding the whereabouts of underground mine workers will facilitate swift intervention in the event of a mining accident. Because underground mining has substantial operating and investment expenses, implementing such a solution must also be practical. The most popular positioning and localisation technology, global positioning system (GPS), is insufficient for indoor environments due to non-line-of-sight (NLOS) situations and poor satellite signal transmission through solid objects. Therefore, GPS cannot be used to position objects in indoor environments. Alternative systems based on ultrasound, Wi-Fi, RFID, visible light, Bluetooth and infrared have been utilised in place of these for a variety of uses and environments (Serhan-Danis et al., 2021; Cavur and Demir, 2022).

In deep underground mines, where activities must be expanded further to extract minerals using underground mining techniques, safety issues must be addressed due to major difficulties with the communication, ground control and mining climate (Onifade et al., 2023a). Alternative positioning systems are used in mining spaces, particularly underground mines that can reach depths of thousands of feet below the earth's surface, because position, navigation, and tracking services centred on positioning systems like GPS are limited to open-space areas where reference signals from satellites are available. Several researches have been carried out on the application of positioning systems to increase productivity and safety during the extraction of minerals (Said et al., 2023; Onifade et al., 2023b). However, there is currently no literature review on the broad deployment of positioning systems in various mining operations stages with consideration on its difficulties and likely workable solutions. As a result, this study offers a distinctive viewpoint on examining the uses, benefits, and difficulties of this technology in the mining industry from a different point of views.

2 Positioning systems

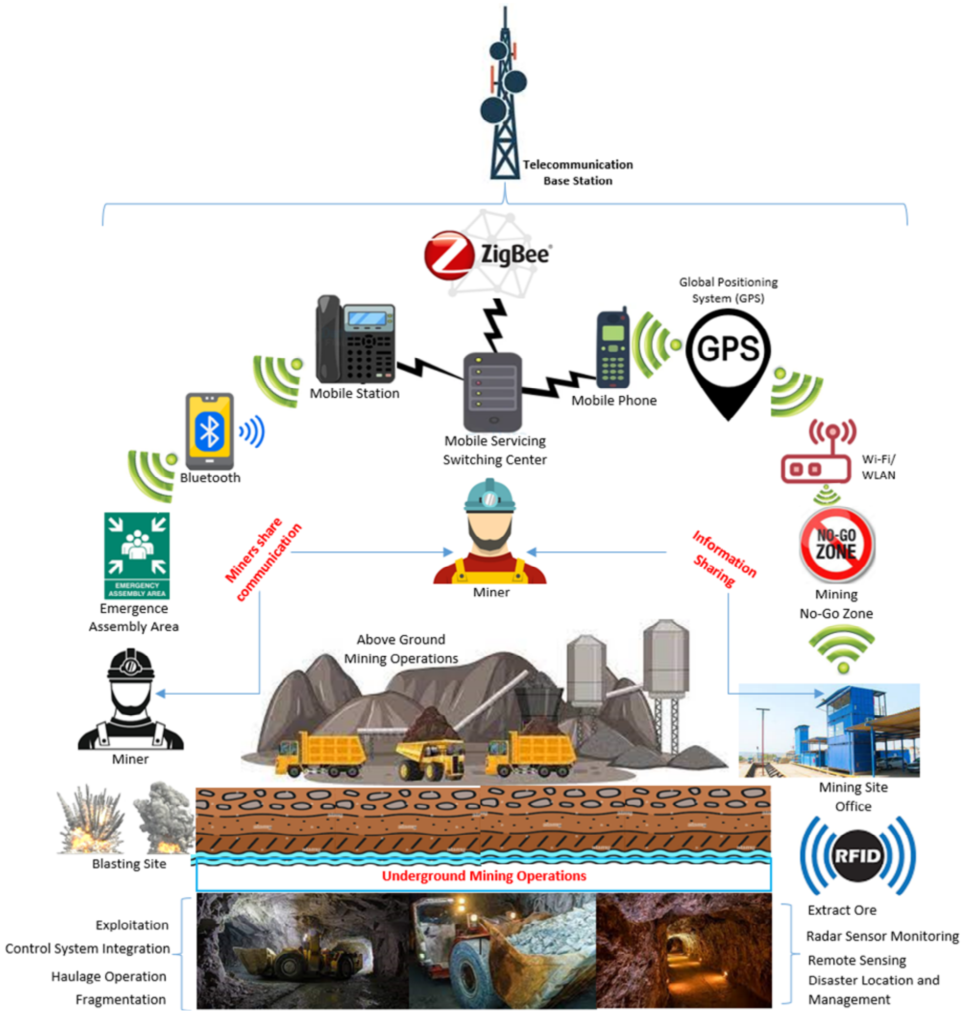
As at 2020, it was possible to find RTLS systems that use Bluetooth low energy (BLE), GPS, RFID, Wi-Fi, UWB, or a combination of those systems. The targeting, environment sensing and modelling, location and motion planning are the main considerations in autonomous vehicles' navigation. The most fundamental of these is location. Positioning is the cornerstone of navigation for autonomous vehicle control systems, and navigation depends on positioning (Chateau et al., 2000). There are many positioning and navigation techniques (visual positioning system, dead reckoning positioning system, radio positioning system, laser positioning system and map-matching location technology) that have been employed because of the complexity of the working environment and the various sensors that are available (Costello et al., 2007). A few underground mine locating systems are also based on inertial navigation system (INS), wireless local-area network (WLAN), RFID, UWB, or a mix of these technologies as indicated Figure 1. There are benefits and drawbacks to each technology. More information on the applications of these positioning systems in the mining industry is provided in Section 3.

2.1 Wi-Fi

Indoor positioning is frequently made possible via Wi-Fi (Ali et al., 2019; Zafari et al., 2019). Several localisation techniques, including angle of arrival (AoA), time of arrival (ToA), and received signal strength indicator (RSSI), can be utilised with Wi-Fi to pinpoint the location of assets (Zafari et al., 2019). Even though they are not often designed to, Wi-Fi networks can be utilised as anchors in a ranging infrastructure for Wi-Fi RTLS. However, this can reduce the accuracy (Zafari et al., 2019).

Wi-Fi is primarily used on smartphones, laptops, and other portable devices, making it a perfect indoor localisation candidate (Kumar et al., 2014; Adebisi and Babatunde, 2022) and one of the most extensively researched positioning breakthroughs in the literature. The precision of localisation can be relatively high, and existing Wi-Fi terminals can be used as a guideline for signal collection. However, existing localisation systems can be established without additional infrastructure. Nevertheless, current Wi-Fi networks are primarily utilised for communication rather than localisation to optimise data transfer and network coverage. Therefore, to increase the precision of their localisation, innovative and effective methods are required.

Figure 1 Applications of positioning systems in mining industry (see online version for colours)



Source: Adapted from Abdulsalam et al. (2023) and Onifade et al. (2023a)

Zhang et al. (2009) suggested the idea of using Wi-Fi in deep mines and explains the requirements needed to build such a system, which includes operational principles, data transfer, software design difficulties and computer systems. Wi-Fi's potential application for finding mobile equipment in a deep coal mine was studied by Ralston et al. (2005). Wi-Fi studies were carried out in a tunnel environment to evaluate some of the main propagation parameters impacting the strength of the received signal. Wi-Fi-based localisation accuracy in deep mine has been found to be of medium precision (5 to15 m) and it may be utilised as a low-level proximity indication or secondary measure for equipment location calculation. Chehri et al. (2006) used the DV-hop algorithm with

Wi-Fi, which is exclusively reliant on the hop distance between a node and anchors for multi-lateration, for an interior localisation solution in deep mines. Through a series of positioning simulations, their largest mistake was 1.3 m.

In real applications, a single barrier coverage frequently fails to deliver the proper service quality due to an attack or sensor malfunction. Consequently, k-barrier coverage, which provides k times the coverage level in contrast to a single barrier coverage, becomes the optimum choice for most applications (Kumar et al., 2005). Fingerprinting techniques, risk assessment method, Wi-Fi and RSSI were all employed by Lin et al. (2014) to analyse the practicability of a real-time tunnel location-based services system. The field-tested recommended positioning algorithm has been utilised to demonstrate that it is steady and accurate (3–5 m) enough to be used as a real-time localisation tool in a tunnel beneath a concrete dam. Yu (2015) used Wi-Fi and the RSSI method to place subsurface miners. In this study, it was suggested to use a layered two-step hidden Markov model to simulate human walking in such circumstances to achieve a tolerable localisation error between 1 and 4 m.

2.2 Bluetooth

The frequency band that Wi-Fi uses is also used by Bluetooth (Thiede et al., 2021; Adebisi and Abdulsalam, 2021). Only RSSI location technology is supported by the underlying technology. However, according to Serhan-Danis et al. (2021), Bluetooth 5.1 can also offer directional information like AoA and AoD. Most of the Bluetooth-based location techniques now in use are simpler and rely on RSS-based inputs. The localisation accuracy of RSS-based inputs has limitations. In its original form, Bluetooth is useful for localisation because of its many benefits, including optimal energy consumption, low cost, and long range. However, recently suggested Bluetooth-based protocols can be utilised for context-aware proximity-based services, such as iBeacon by Apple and Eddystone by Google. A Bluetooth beacon-based underground navigation system (BBUNS) was developed by Baek et al. (2017), and its primary duties include determining the optimal route through a deep mine, monitoring the positions of dump trucks, and showing this information on mobile devices. They developed a 3D GIS database for a total of 50 Bluetooth beacons that were placed beside haul highways. The Bluetooth beacon system installed in the underground mine was used to develop an Android-based BBUNS application that allows users to view each dump truck’s current location and the quickest route to their destination. They used the RSSI algorithm to explore an underground mine for equipment and vehicles. The dump truck’s engineered structure is constrained by delays in visualising its current location and the best path to its goal in the underground mine.

2.3 RFID

According to Chawla and Ha (2007), several industries, including logistics, surveillance, etc., are increasingly adopting RFID technology for real-time item identification. The least priced RFID tags with the highest economic potential are passive or semi-passive tags, which derive their energy from the reader’s signal or their surroundings. Passive RFID tags adjust their antenna reflection properties in response to information inputs using backscatter modulation. A well-known location sensing system utilising RFID technology is SpotON (Hightower et al., 2000), which uses an aggregation technique for

3D position sensing based on the RSS analysis. LANDMARC is a different system that makes use of active RFID (Ni et al., 2004; Okegbile et al., 2020). Future RFID systems will need to manage many tags, be extremely small, light, and affordable, and have accurate real-time localisation at the sub-metre level. These demands, however, cannot be met by first- and second-generation RFID (Chon et al., 2004), as well as wireless sensor network technologies built on ZigBee technology.

In order to position people and vehicles in underground locations, this technology has been frequently used (Mishra et al., 2014). The main benefits of RFID, which set it apart from competing technologies for the same use, are responsible for this wide-ranging adoption. In order to follow people and vehicles in underground mines, Wojtas and Wiszniowski (2012) developed an experimental navigation system that combines RFID sensor fusion with an augmented reality user interface. Zheng et al. (2019) experimented with personnel locating in an underground coal mine roadway using RFID tags and the TDoA method. The average localisation accuracy in this experiment ranged from 1.5 to 2 m. The Pollyanna No. 8 Mine in Oklahoma served as the topic of a feasibility study on the application of indoor locating technology by Radinovic and Kim (2008), with a focus on the RFID option. By utilising TDoA and RSSI positioning approaches, they conducted a cost study of setting up RFID or other wireless tracking systems at this mining site and evaluated the benefits of having such a service. Several multi-kilometre runs of an RFID-based locating system in the network of underground tunnels at Carleton University were completed successfully (Rusu, 2011; Rusu et al., 2011).

2.4 ZigBee

Based on the IEEE 802.15.4 specification, ZigBee is a proximity wireless, low-data-rate and low-power network (Baronti et al., 2007). The technology is intended to be less expensive and simpler to use than current communication technologies like Bluetooth and Wi-Fi. ZigBee is ideal for placing sensors within WSN, but because it is often unreachable on most mobile devices, it is unfavourable for situating indoor users (Zafari et al., 2019). Huang et al. (2010) proposed a network RSSI algorithm with an improved ZigBee base for an underground mining positioning system. In their system, the Ethernet and ZigBee sub-networks, which act as significant data transmission channels, are used to provide localisation data to the surface, and the surface server offers the service to show the user the dispersion of miners in the e-map via a browser. Liu et al. (2010a, 2010b) created a hierarchical coal mine personnel positioning system (MPPS) based on WSNs and ZigBee technologies, with a focus on location in blind areas. Additionally, they put into place an upper supervisory program that included technologies for data retrieval, storage, viewing, and collection. They also created a remote monitoring application to track the network's current state in real-time, which includes the status of reference nodes, gateways, local nodes, and details on the whereabouts of mobile miners.

Wang et al. (2010) established a conceptual framework for the real-time localisation and monitoring of coal miners by using ZigBee self-organised sensor networks. They first developed a theoretical approach to deal with output volatility using an RSSI-based localisation algorithm, which demonstrated a 25% reduction in average localisation error when compared to a normal weighted centroid technique. They applied the suggested method into practice in China's XinAn Coal Mine. Song and Qian (2016) introduced an improved sequence-based localisation method for deep coal mines that is coupled with quantum-behaved particle swarm optimisation and makes effective use of the query efficiency of the best global solution. In their simulations, they used ZigBee devices to build WSNs and find persons. Zhang and Su (2013) used the RSSI algorithm with ZigBee technology to establish a position system for deep mines. They employed the CC2431, a real System-On-Chip for ZigBee wireless sensor networking solutions that offers distance precision of about 3 m or less at low total cost of ownership.

2.5 Visual positioning system

Visual localisation technology uses a CCD camera to detect the surrounding environment. The scraper can determine its position by detecting and tracking a number of locations with evident qualities, then combining them with the location data of a particular scene. The technique displays very accurate positioning. However, the underground tunnel's physical environment, including the light, makes actual image capturing challenging (Zare et al., 2021; Okegbile et al., 2022).

2.6 Dead reckoning positioning system

Dead reckoning is a system for autonomous positioning and navigation. Projections can be made using scrapers' own location and velocity information, and it is mostly influenced by external environmental factors. The equipment must, however, be periodically adjusted because dead reckoning errors build up over time (Beliveau et al., 1996). A scraper's location as determined by the installed sensors is first considered via the dead reckoning method before the position is calculated. The speed and heading angle of the scraper aircraft must be measured in real-time for this technique to work. Double differential odometers and angular rate gyroscopes are the instruments that are most frequently used to measure heading angle, while the Doppler radars, odometers and accelerometers are used to measure speed (Beliveau et al., 1996).

2.7 WLAN

In public hotspots and commercial settings, the use of WLAN standards that operate in the 2.4 and 5 GHz ISM band has grown significantly during the past ten years. It is now being used in mining and other automated industrial processes. WLAN normally has a range of 50–150 m and a gross bit rate of 1-108 Mbps, depending on the situation. An existing WLAN infrastructure can be used for indoor location by including a location server. The conventional WLAN positioning system using RSS has an accuracy range of 2 m and greater and an update rate of a few seconds. The accuracy of position estimations based on the RSS of WLAN signals is affected by a variety of indoor environment factors, such as movement and direction, overlapping of access points, doors, etc. (Lui et al., 2011).

2.8 Map-matching location technology

In map-matching technology, a mounted image acquisition equipment (CCD camera) stores environmental data and digital maps in the scraper. By comparing the real-time environment data with the previously recorded map data, the camera captures surrounding data in real-time. The matching's purpose is to locate the scrapers in real-time and determine several traits shared by the two points of information. However, the initial location information is needed for map matching. This method by itself cannot be used for accurate positioning because the underground tunnel in the digital map information is continually changing.

2.9 Laser positioning system

To calculate distance, a laser rangefinder primarily counts the number of times light is emitted onto an object's surface and returned to it. Laser rangefinders can measure things accurately because of their extended range, increased precision, faster transmission speed and various item forms, colours, and materials. Laser rangefinders can offer a variety of high-frequency, precise distance data. The placement of the scraper on the laser radar allows the laser rangefinder to accurately determine beacon location, as well as calculate its own position and mobility status (Alici and Shirinzadeh, 2005).

2.10 INS

Inertial navigation uses measurements of acceleration and angular velocity to track the position and orientation of a mobile device when the beginning position and orientation are known. A complete INS normally consists of an inertial measurement unit that measures acceleration and angular velocity and a computer that does the computations. This type of navigation is used by a wide range of applications, including ships, airplanes, robotics, etc. according to Titterton and Weston (2004). To identify the orientation and location of the mobile unit, an INS's basic operation is to double-integrate the acceleration and integrate the angular velocity. An underground positioning system based on WLAN or UWB can be improved by the addition of an inertial navigation system. By incorporating INS data into the positioning system, directionally dependent disturbances may be adjusted for. Additionally, it increases the dynamic range of the combined system and helps eliminate shadow areas (De Angelis et al., 2010).

2.11 GPS

Early in the 1970s, the American Department of Defense developed the GPS, a satellite-based navigation system. The American military was the original target audience for the development of GPS. It later became available to civilians, though, and as a result it now performs a dual function and is used by both military and civilian users. GPS gives real-time positioning and timing information in any location and condition. One-way-ranging (passive) GPS is still used for security because it can accommodate an indefinite number of users (Ruff, 2006; Said et al., 2023).

The geographic information system (GIS) is one sort of computer system for gathering, storing, managing, analysing, displaying, and using geographic information. It is a comprehensive system that is capable of handling and analysing enormous amounts of spatial data. The application of GIS in the creation of a range of spatial databases and decision support systems, each with its own set of criteria, has addressed numerous diverse formal spatial inquiries, spatial analyses, assistance plans, and decision-making activities. GIS has so far been steadily adopted in open pit mines, according to Liu et al. (2004). A dynamic management system for ore blending in open pits, which primarily relies on spatial geographic data, oversees tracking, monitoring, and managing production equipment. As a result, GIS is crucial for decision support, real-time dynamic management and visual ore blending supervisory systems.

Sun and Nieto (2009) claim that the Google-Earth (GE) interface of the assisted driving system (ADS) combines dynamic zooming based on the GE 3D model of the Earth with surface images obtained from satellite photos and aerial photography. ADS switches from GE maps to previously loaded AutoCAD maps when zooming in on a specific mine. The quality of the graphic information provided to the operator and system manager is enhanced and improved by this technique. GE is a cutting-edge piece of free software that has the potential to be a strong foundation for geographic data for programs like ADS. The study indicates that the ADS is the first system that has been put forth for mining and earth moving activities that combines GE with dynamic equipment GPS tracking, using local AutoCAD maps to supplement graphic information in GE. In addition, Gu et al. (2010) reported that a dynamic management system for ore blending in an open pit mine has been created by using the GIS, GPS, and general packet radio service (GPRS). In a practical application, a linear program was established. The study found that the system is particularly effective at automatically creating a daily production plan for mixing ore, and it continuously checks and regulates the mining production process.

2.12 UWB

Future short-range indoor radio frequency communication uses UWB, a rapidly developing technology. This system offers services at extremely high bit rates, uses little power, and is capable of accurate positioning (Ziegler et al., 2023). The use of UWB technology for commercial purposes in the USA in the frequency range of 3.2 to 10.6 GHz was regulated by the Federal Communication Commission (FCC) in 2002 (Xu and Yang, 2008). For indoor applications, UWB is a relatively recent and promising localisation technology. Since UWB pulses have a short length (less than 1 ns), they are less prone to interference and have a higher degree of accuracy than other positioning systems like WLAN (Zhang et al., 2006; Hancke and Allen, 2006). This enables the original signals to be separated from the reflected signals before filtering. With inter-sensor measurements like AOA and connectivity, distance, time difference of arrival (TDOA) and TOA, WSN localisation methods are used to calculate the locations of the sensors in a network whose positions are initially unknown. WSN localisation techniques are used in a wide range of applications, including inventory management intrusion detection, road traffic monitoring, health monitoring, reconnaissance, and surveillance. Other applications include animal habitat monitoring, bush fire surveillance, water quality monitoring, and precision agriculture (Ziegler et al., 2023).

Cheng (2012) provides a localisation method based on UWB and TOA for monitoring and tracking the locations of people or vehicles in coal mine environments. He first presented the ZigBee-RSSI positioning system and afterwards suggested a TOA-based UWB localisation system based on WSN for a coal mine. The study found that RSSI-ZigBee in coal mines has lower accuracy than TOA-based UWB localisation system. Chehri et al. (2009) carried out a pilot experiment to test if UWB-based WSN could be used to locate in underground tunnels through simulation and measurements. They established the computing requirements for the installation of such a system in an underground mine through their simulations, which considered the ToA technique for localisation. Zhu and Yi (2011) proposed a TDoA/RSSI hybrid positioning algorithm for exact placement of an underground mining sensor in a network of identified beacons using a UWB platform. In comparison to beacon readings, their hybrid approach increased positioning accuracy, and simulation results with the UWB arrangement showed good performance. To evaluate a UWB system for use in placement in underground mines, Li et al. (2016) evaluated it in an indoor environment. With a normal measurement inaccuracy of between 10 and 20 cm, the largest range was up to 100 m. However, their findings indicated that the thickness of the wall may have an impact on the range measurement error. The UWB signal could pass through walls to provide angle readings.

3 Implementations of positioning systems in the mining industry

To increase worker safety, operational visibility, and resource efficiency in mining operations, RTLS technology is essential. Mining is a difficult industry with many dangers and hazards. To secure the safety of employees and the effective extraction of priceless resources, the mining environment especially the underground mine presents special obstacles that call for creative solutions (Onifade et al., 2023a). Real-time tracking and monitoring capabilities provided by RTLS technology allow mine operators to reduce hazards, streamline processes, and boost overall production. This section examines some essential components of how RTLS enhances safety in the mining industry.

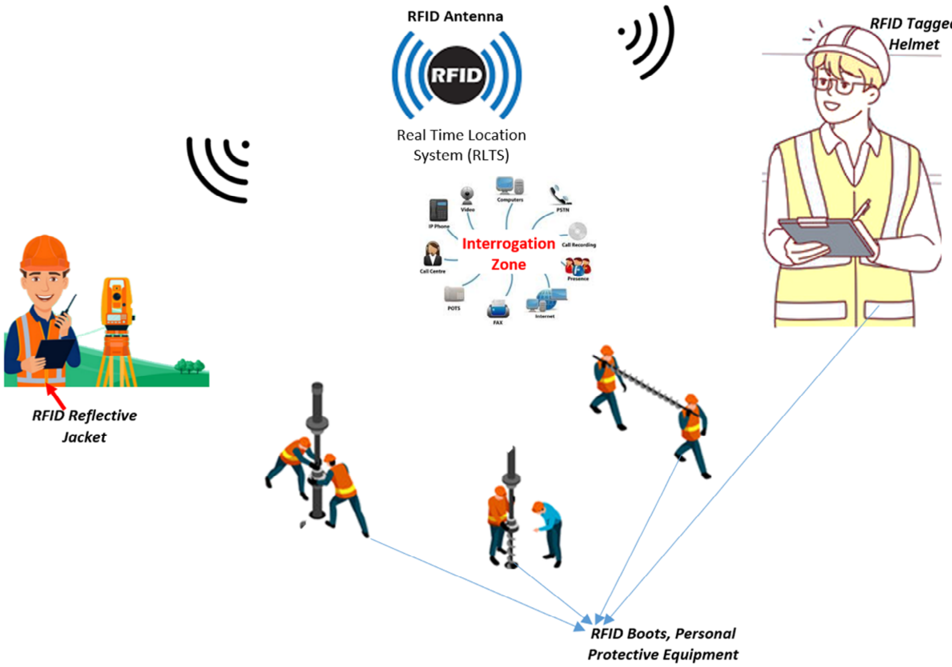
3.1 Enhanced personnel tracking, management and monitoring

RTLS makes it possible to precisely track and monitor underground mine miners, assuring their safety and welfare. Their whereabouts can be precisely identified in real-time by providing miners with wearable RTLS tags or incorporating the technology into their personal protective equipment (PPE) as indicated in Figure 2. This knowledge is crucial in a disaster because it enables rescue personnel to discover and help workers who are in need right away. RTLS systems give users insights into resource and human management, increasing output and improving processes. Operators can increase overall operational efficiency, pinpoint bottlenecks and boost task distribution by monitoring real-time data on worker movements. Additionally, the information gathered from RTLS systems can help with resource planning, ensuring that essential supplies and resources are accessible when and where they are required. Rath et al. (2024) explore the use of internet of things through real-time monitoring to achieve operational efficiency.

3.2 Active hazard mitigation

RTLS systems make it possible to proactively identify and address potential risks in underground mines. Szrek et al. (2020) report on the application of RTLS systems to mitigate hazards related to belt conveyors used in underground mining. Operators can quickly identify harmful situations or behaviours by gathering real-time data on worker movements, ambient variables and equipment use. This makes it possible for them to take preventative action to reduce or eliminate hazards before accidents happen.

Figure 2 Personnel tracking and monitoring using positioning systems (see online version for colours)



3.3 Response to emergencies and evacuation

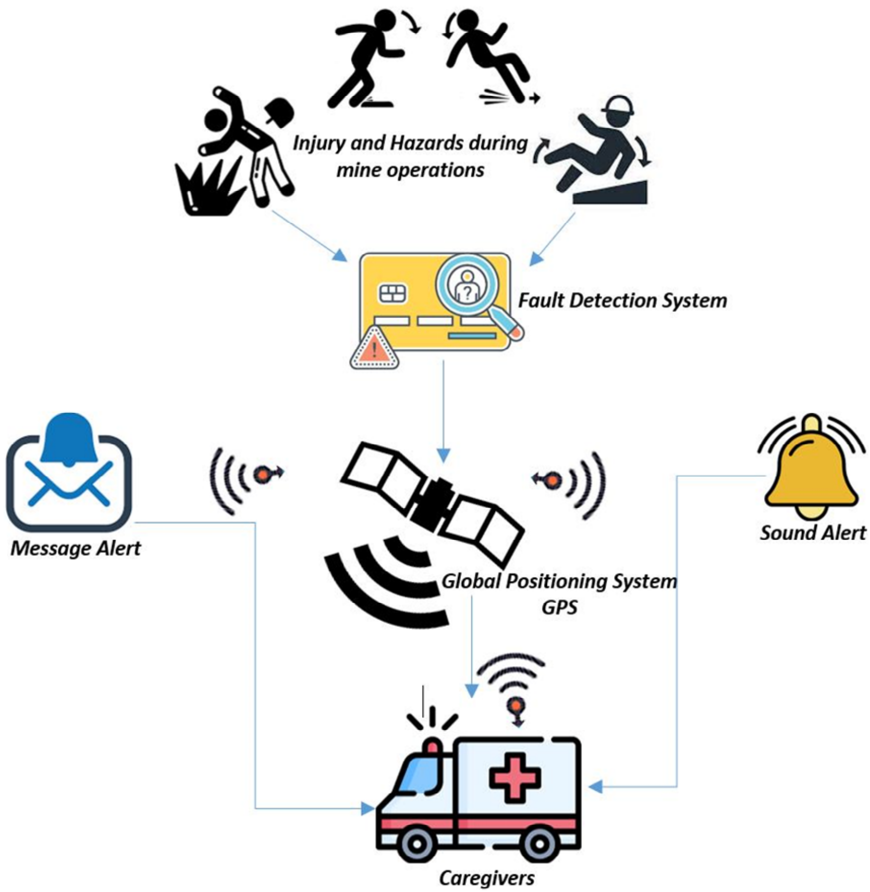
RTLS technology enables quick emergency response and evacuation protocols in the case of an emergency, such as a collapse or a gas leak. Rescue crews are better able to reach impacted areas quickly and conduct their task effectively when they can pinpoint the position of the personnel. The RTLS's real-time visibility increases the likelihood of a successful rescue and reduces potential casualties.

Injuries and accidental falls are frequent hazards in underground mines (Paul and Maiti, 2007; Sherrigton, 2020; Alessa et al., 2020). When a fall is detected, RTLS technology can send out automatic alerts to adjacent employees or the control room. Man-down notifications make sure that the injured worker can get help right away, potentially saving lives and lessening the severity of injuries. A typical architecture around this illustration is provided in Figure 3.

3.4 Geofencing and monitoring of restricted zones

For creating fictitious boundaries and controlling access to limited regions within the mine, RTLS systems make use of geofencing capabilities. An alarm is set off if a worker or vehicle enters a restricted area, guaranteeing adherence to safety procedures and preventing unauthorised entry to dangerous locations. Geofencing helps prevent accidents by limiting access to high-risk regions like those with unstable rock formations or vulnerable to gas leaks. Woolsey (2022) notes that georeferencing is a novel technology which can be used to mitigate mining hazards related to mining blast zones.

Figure 3 Response to emergencies and evacuation using positioning systems (see online version for colours)



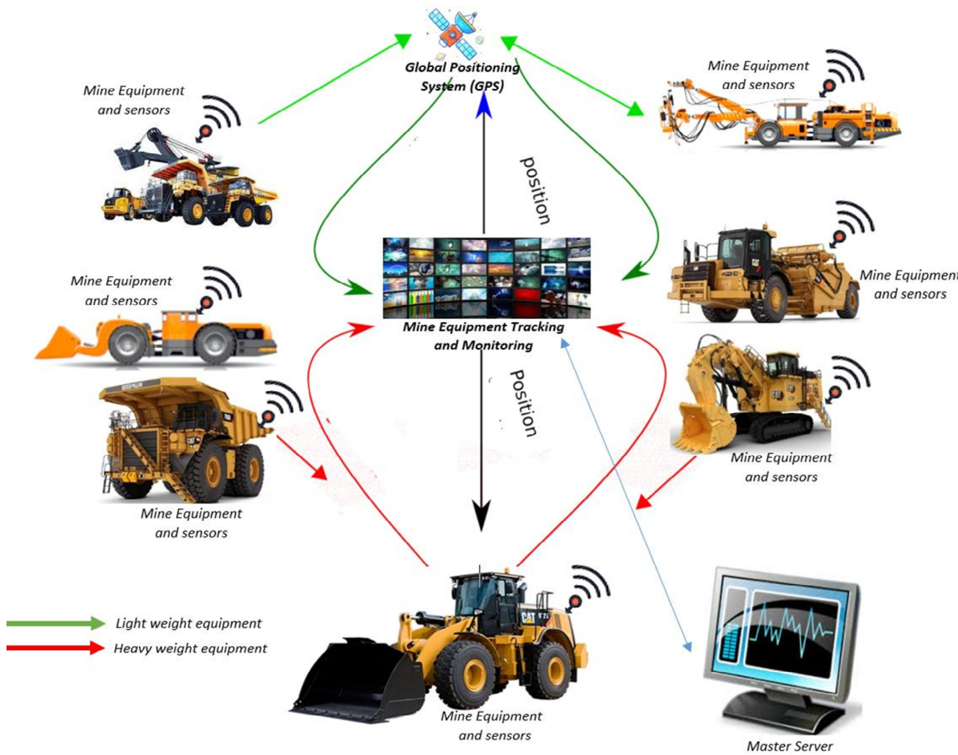
3.5 Safety and training compliance

In underground mines, RTLS systems also help with safety compliance and training initiatives. Operators can build focused training programs to address certain safety issues by evaluating the data gathered from the system to spot patterns, pinpoint areas of concern, and detect patterns. This data-driven strategy promotes a culture of continuous improvement among the mining workers and raises safety awareness. Lin et al. (2014) developed an RTLS system which uses an algorithm based on Wi-Fi fingerprinting to mitigate safety risks for tunnelling workers.

3.6 Equipment tracking, utilisation and maintenance

Accurate tracking and monitoring of mining equipment, including machinery, tools and vehicles and tools, is made possible using RTLS technology (Radinovic and Kim, 2008; Kianfar, 2022; Nguyen and Ha, 2023). Operators can get real-time visibility into the location, use, and performance of their equipment by tagging it using RTLS. Absolute monitoring of equipment and their operators based on current location and real-time usage can be enhanced with an excellent positioning system as shown in Figure 4. Beyond information sharing, network connected screens are also used to initiate actions where necessary. This information makes it easier to minimise equipment downtime, allocate equipment effectively, and schedule preventative maintenance, all of which increase productivity.

Figure 4 Positioning system for tracking mine equipment (see online version for colours)



To improve equipment maintenance schedules, RTLS systems can relate to solutions for predictive maintenance. Operators can predict probable failures or maintenance requirements by continuously monitoring equipment performance and gathering data on variables like usage, vibration and temperature. This proactive strategy lowers maintenance costs, increases equipment lifespan, and prevents unscheduled downtime.

3.7 *Asset record and monitoring*

For mining operations to be effective, an accurate asset inventory must be kept. Real-time asset tracking is made possible by RTLS technology, which also reduces human error by doing away with manual inventory management procedures. Setiawan and Sunitiyoso (2012) provide a practical and innovative case of planning and execution of a personnel and asset tracking system in real-time for underground mining operations, focussing on the PT Freeport mining operations. Mine operators may quickly discover equipment or supplies, saving search times and increasing operating efficiency, by automatically tracking the location and movement of assets.

3.8 Workflow improvement

The use of RTLS technology enables mine operators to streamline processes and reduce inefficiencies by offering insightful data on worker interactions and movements. Operators can pinpoint regions with workflow bottlenecks, put process enhancements into place, and improve job sequencing by analysing the data gathered. Operations are streamlined, idle time is decreased, and total productivity is raised. Fang et al. (2021) provide an optimisation technique for RTLS to enhance underground mining workflow.

3.9 Environmental and energy efficiency

In underground mines, RTLS systems can help increase environmental and energy efficiency (Kianfar, 2022; Ayres da Silva et al., 2023; De Felice and Petrillo, 2024). Operators can find opportunities for energy optimisation and put waste-reduction strategies in place by tracking and analysing energy consumption patterns. To ensure ideal air quality and reduce energy consumption without compromising worker safety, RTLS technology may also help monitor and manage ventilation systems.

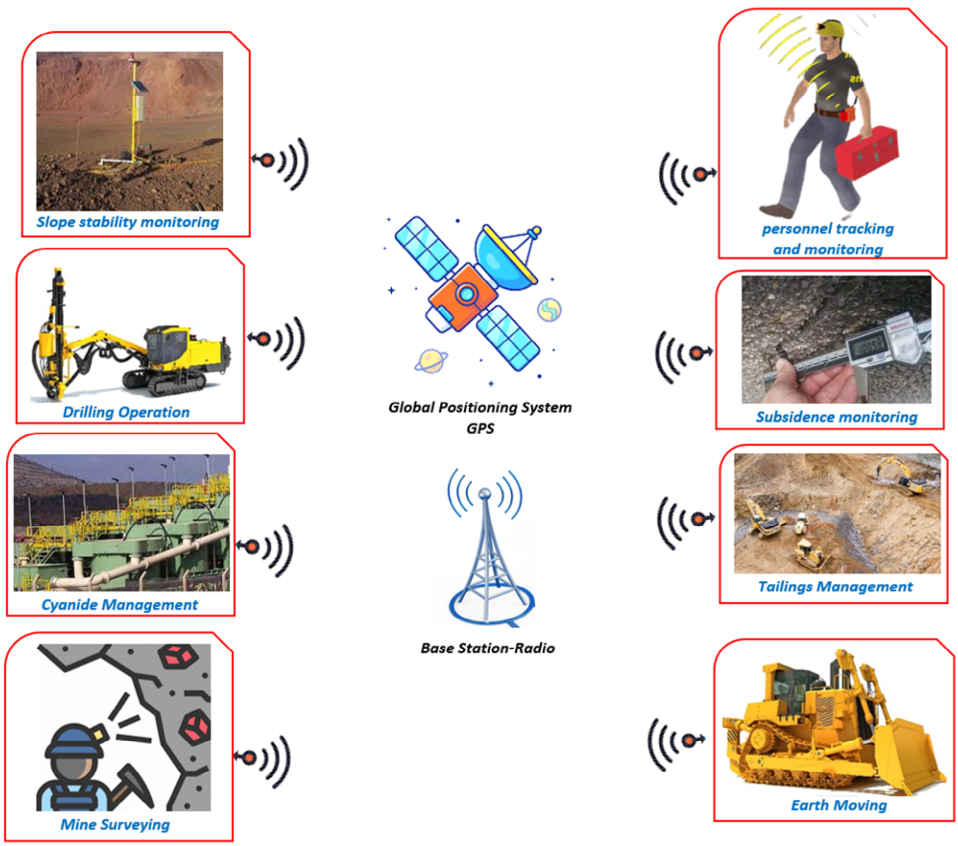
4 Practical use cases of positioning systems in the mining industry

In mining environments, positioning is essential for maintaining mine workers' safety. The capacity to resolve mine productivity constraints, which have a significant economic impact, is another crucial technological capability. A major goal of the mining sector is to eliminate all risks in every workplace by ongoing development, rigorous training, the adoption of cutting-edge work procedures, and the introduction of new technologies. Kiziroglou et al. (2016) and Duarte et al. (2022) provides a comprehensive technical coverage of different types of sensors which can be deployed in the mining industry to enhance safety and productivity. It is also vitally important to assess the value added by positioning systems to mining projects by using performance evaluation techniques like evaluate project performance (EVA). The Eva technique is covered in detail by Ugural and Burgan (2021). The use cases of positioning system in the mining industry is discussed in this section and illustrated in Figure 5.

4.1 Personnel tracking

Personnel tracking using positioning systems has emerged as a critical technology to enhance safety by providing real-time location information for miners in the mining industry (Rácz-Szabó et al., 2020; Cavur and Demir, 2022; Sadeghi et al., 2022). The significance of personnel tracking in the mining industry is amplified by the complex environments in which mining take place. Mining operations often take place in remote and challenging environments, including underground mines, open-pit mines, and exploration sites. These settings present numerous safety challenges. Underground mines can be labyrinthine as they consist of confined spaces, posing navigation challenges and increasing the risk of getting lost. Miners may encounter hazardous materials such as toxic gases, explosives, or unstable geological conditions, making quick response to emergencies crucial. Mines feature heavy machinery and equipment, increasing the risk of accidents involving miner workers and vehicles as a result of miners-equipment interactions (Lv et al., 2011). Environmental factors such as adverse weather conditions, high altitudes, and extreme temperatures can affect miner's health and safety. In the event of accidents, timely rescue and evacuation are critical for minimising harm. Many mining operations must comply with stringent safety regulations and reporting requirements.

Figure 5 Use cases of positioning system in the mining industry (see online version for colours)



Personnel tracking using positioning systems address these challenges by providing real-time location data, enabling efficient response to emergencies, optimising worker safety, and ensuring compliance with safety regulations as shown in Figures 2 and 3. Various positioning technologies are employed in personnel tracking systems for mining safety (Zare et al., 2021; Onifade et al., 2023b). GPS relies on satellites to pinpoint a user's location. In open-pit mines and surface operations, GPS is highly effective for tracking miners' movements. RFID systems use radio waves to identify and track tags attached to personnel as indicated in Figure 2. RFID is suitable for both underground and surface mining, providing accurate, real-time data. Wi-Fi and Bluetooth-based systems utilise Wi-Fi or Bluetooth beacons to track miners' locations within a defined area, such as an underground mine. UWB technology offers precise location tracking by measuring the time it takes for signals to travel between devices.

In the event of an accident, such as a cave-in or gas leak, personnel tracking systems enable rapid response. Emergency teams can pinpoint the exact location of trapped or injured miners, expediting rescue efforts. Positioning systems can issue proximity warnings to miners and equipment operators when they approach hazardous areas or get too close to heavy machinery, preventing accidents (Patrucco et al., 2021; Imam et al., 2023). Mining operations often need to comply with safety regulations that require the tracking of miners' locations and the ability to produce historical location data for audits and reporting. Geofencing defines virtual boundaries within a mine. If a miner breaches these boundaries, alerts are triggered, ensuring they stay within designated safe zones. Geofencing technology is applied to dangerous areas within mines, such as blast zones or unstable geological formations (He et al., 2021; Jha et al., 2022).

There are several practical examples which highlight the application of personnel tracking in the mining industry (Isleyen and Duzgun, 2019; Seguel et al., 2021). Since underground mines are complex and hazardous environments, miners wear RFID-enabled tags that continuously transmit their location to a central monitoring station. If a miner enters a prohibited area or stops moving for an extended period, an alert is generated, enabling a swift response. For instance, if a miner is injured or trapped, rescue teams can locate them precisely using the tracking system. In open-pit mines, GPS tracking systems are used to monitor the movements of operators of heavy machinery and mining trucks as shown in Figure 4. If a mining vehicle approaches a pedestrian worker, both the vehicle and the worker receive alerts, reducing the risk of collisions. GPS also assists in optimising routes for haulage vehicles to minimise travel in high-risk areas. In emergencies, such as a fire or gas leak, miners can quickly navigate to designated safe zones using GPS or RFID tags. Emergency responders receive real-time location data to facilitate the evacuation process.

4.2 Subsidence monitoring

The importance of subsidence monitoring in the mining industry can never be overstated. Subsidence is an inherent consequence of underground mining, especially in longwall and room-and-pillar mining methods. It occurs when the removal of underground minerals weakens or collapses the overlying rock layers. Surface subsidence can damage infrastructure, leading to structural failures, sinkholes, and road collapses (Strozik et al., 2016; Suh and Choi, 2017). These hazards endanger not only mining personnel but also communities near mining sites. Subsidence can disrupt ecosystems, alter surface water drainage patterns, and damage wetlands. The subsidence-induced changes to the landscape can be irreversible, affecting biodiversity and water resources.

While the mining industry is a critical driver of global economic development, providing essential resources for countless industries, the mining activities can result in subsidence – a gradual settling or sinking of the earth's surface – which poses significant risks to both safety and the environment (Baek et al., 2008; Zvarivadza, 2016). Subsidence can lead to infrastructure damage, loss of biodiversity, and even human displacement. To mitigate these risks, positioning systems have become indispensable tools for subsidence monitoring in mining operations. These systems utilise technologies like GPS, interferometric synthetic aperture radar (InSAR), LiDAR and global navigation satellite system (GNSS) to track ground movements with precision.

Positioning systems in subsidence monitoring leverage a range of technologies (Salam and Salam, 2020; Ma et al., 2022, 2023; Liu and Zhang, 2023). GPS and GNSS receivers on the earth's surface track ground movements by comparing their positions to a network of satellites. These systems offer high precision and can provide real-time data. InSAR uses radar waves from satellites to measure surface deformation. It is particularly useful for monitoring large areas and detecting millimetre-scale movements. LiDAR systems create detailed 3D maps by sending laser pulses to the ground and measuring the time it takes for the pulses to return. Ground-based sensors, such as tiltmetres and extensometers, are placed in strategic locations to directly measure ground movement.

There are several practical examples of subsidence monitoring in the mining industry through the use of positioning systems (Park and Choi, 2020; Sidki-Rius et al., 2022). In longwall mining, where large sections of coal are removed, subsidence can result in significant surface movements. GPS and InSAR are used to continuously monitor subsidence and provide real-time data to mine operators. This allows for adjustments to mining operations to minimise surface impacts. Open-pit mining can also induce subsidence, especially when large voids are left underground. LiDAR surveys are employed to create detailed 3D models of the pit and detect any subsidence-related deformation. This data informs pit design and safety measures. In ecologically sensitive areas, LiDAR and ground-based sensors are used to monitor subsidence's impact on ecosystems. Data collected aids in designing measures to protect and preserve biodiversity. Subsidence can disrupt groundwater flow, leading to issues such as flooding or altered water quality. InSAR and GPS help monitor these changes, allowing for timely intervention to protect water resources.

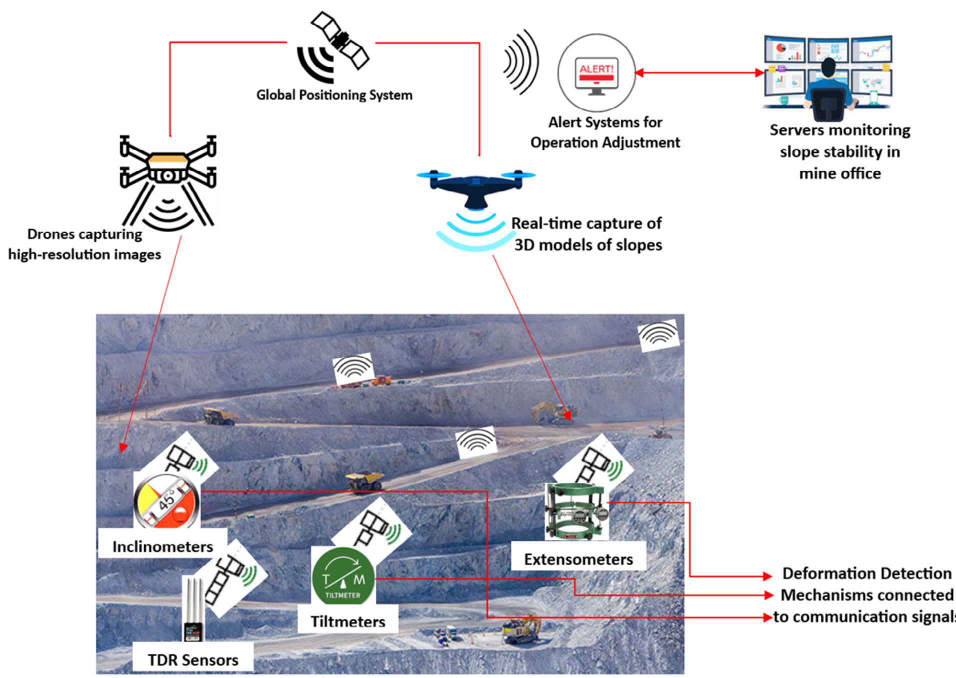
The implementation of subsidence monitoring systems provides early warnings, minimising risks to both mining personnel and nearby communities. Predictive data derived from subsidence monitoring allows mining companies to plan for infrastructure repairs and associated costs and reducing economic impacts. Accurate subsidence data facilitates compliance with safety and environmental regulations, averting potential legal and financial consequences (Krzemień et al., 2016).

4.3 Slope stability monitoring

The excavation of minerals and ores often involves the creation of steep slopes, which, if unstable, can lead to disastrous consequences (Zvarivadza, 2015; Moloi and Zvarivadza, 2016; Mametja and Zvarivadza, 2017; Segaetsho and Zvarivadza, 2019; Williams et al., 2021). Unstable slopes pose a severe risk to mining personnel working in and around these areas. Slope failures can result in loss of life, damage to equipment and infrastructure, and environmental harm. To mitigate these risks, mining companies employ positioning systems for slope stability monitoring, utilising technologies such as GPS, LiDAR, and InSAR as illustrated in Figure 6. These systems offer real-time, high-precision data that enables proactive safety measures and environmental protection.

Positioning systems for slope stability monitoring capitalise on various technologies (Gray, 2021; Sahay and Vladut, 2022). GPS and GNSS receivers provide precise location data for monitoring the movement of slope features and ground deformation. LiDAR scanners create detailed 3D maps of slope surfaces, enabling the detection of subtle changes in topography indicative of instability. InSAR utilises radar signals from satellites to measure ground deformation with millimetre-scale accuracy. It is particularly valuable for large-scale slope monitoring. Tiltmetres, extensometers, and inclinometers are installed on or within slopes to directly measure ground movement. Drones equipped with LiDAR or photogrammetry technology can capture high-resolution images and 3D models of slopes, facilitating monitoring.

Figure 6 Case uses of positioning systems for slope stability monitoring (see online version for colours)



Several practical examples can be used to illustrate how positioning systems are applied to slope stability monitoring in the mining industry. In open-pit mining, the stability of high, steep slopes is critical. LiDAR and GPS systems are employed to create 3D models of slopes. Frequent scans track any changes in slope angles, enabling early detection of instability. For example, if LiDAR data reveals a sudden steepening of a slope, it triggers alarms for immediate intervention. In underground mining, tunnels and chambers can weaken surrounding rock, potentially leading to subsidence or slope instability (Bell et al., 2005; Wang et al., 2015; Jiang et al., 2017; Wang et al., 2020; Tegachouang et al., 2022). InSAR satellites continuously monitor ground deformation above underground workings. If significant deformation is detected, miners are alerted, and operations may be adjusted or halted. Slope stability is crucial for tailings dams. GPS and inclinometers installed on dam walls monitor their stability in real-time. If sensors detect even minor movement, automated systems initiate safety measures, including controlled releases of water to relieve pressure. Steep haul roads are common in mining. GPS-equipped haul trucks continuously relay their positions to central monitoring systems. Algorithms analyse data to assess road stability. If excessive ground movement is detected, trucks are rerouted to safer paths.

The use of slope stability monitoring systems has various advantages. Early warnings and rapid response measures significantly enhance the safety of mining personnel and nearby communities. Monitoring systems help prevent or mitigate environmental damage, preserving ecosystems, water resources, and soil quality. Predictive slope monitoring data enables mining companies to plan maintenance and safety measures efficiently, reducing economic losses. Accurate slope stability monitoring data facilitates compliance with safety and environmental regulations, avoiding potential legal and financial consequences. Continuous slope stability monitoring minimises operational disruptions, ensuring consistent production and reducing financial risks.

4.4 Tailings management

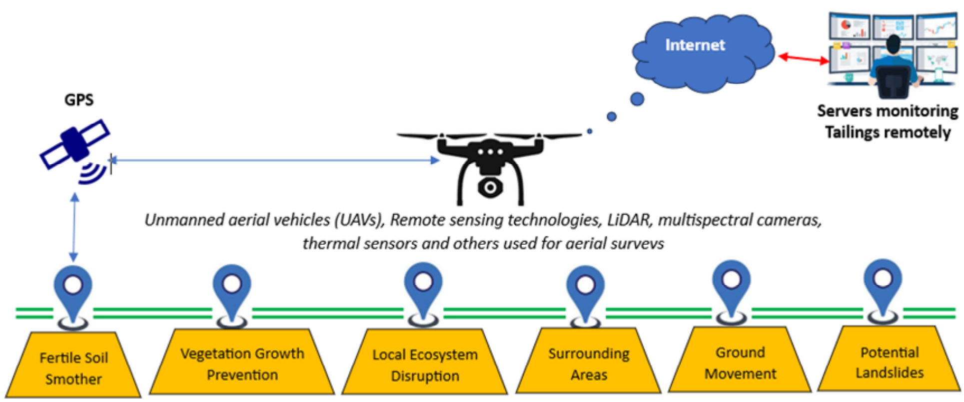
One of the most critical aspects of mining operations that demands careful management to enhance safety and environmental protection is the disposal of tailings (Li et al., 2018b; Lin et al., 2022). Poorly managed tailings can result in a range of disastrous consequences. The release of toxic substances from tailings can contaminate soil, water bodies, and ecosystems, causing long-lasting ecological damage and environmental degradation. Tailings often contain heavy metals and chemicals that, when released into water bodies, can harm aquatic life, and affect downstream communities. Improperly designed and managed tailings dams can collapse, leading to catastrophic landslides and floods, as seen in the Brumadinho dam disaster in Brazil in 2019 (Rotta et al., 2020; Lazorenko et al., 2021). Managing these tailings is a complex and multifaceted task that directly impacts the safety of mining personnel, nearby communities, and the environment.

There are several direct environmental and safety concerns related to tailings management in the mining industry, calling for effective use of positioning systems (Adiansyah et al., 2015; Jarvie-Eggart, 2015; Hui et al., 2018). The seepage or breach of tailings dams can lead to the release of pollutants into rivers, lakes, and groundwater, contaminating drinking water sources and aquatic ecosystems. Exposure to tailings can result in health issues such as heavy metal poisoning, respiratory illnesses, and skin conditions for those living or working near mining operations (Lazorenko et al., 2021). Tailings dam failures can lead to infrastructure destruction, including roads, bridges, and buildings, resulting in economic losses and potential losses of life.

To address these concerns, the mining industry is increasingly turning to advanced technologies like positioning systems to monitor, manage, and mitigate the risks associated with tailings. Unmanned aerial vehicles (UAVs), commonly known as drones, equipped with remote sensing technologies such as LiDAR, multi-spectral cameras, and thermal sensors, are used for aerial surveys, terrain modelling, and monitoring of tailings facilities and surrounding areas. GPS-equipped sensors can continuously track ground movement, allowing early detection of potential landslides or dam failures in tailings facilities. GIS plays a critical role in emergency preparedness and response by providing real-time spatial information during crises like dam failures or natural disasters. Drones perform aerial surveys by capturing high-resolution images and LiDAR data to create 3D terrain models, aiding in tailings dam slope stability analysis and facility design. Multi-spectral cameras on drones can detect changes in vegetation health, water quality, and land use in the vicinity of tailings facilities (Jackisch et al., 2018; Shahmoradi et al., 2020; Said et al., 2021). Drones equipped with thermal cameras conduct real-time monitoring and can identify temperature anomalies, helping identify issues like seepage or hot spots in tailings dams.

Tailings monitoring and surveillance involve continuous tracking and assessment of tailings facilities to identify potential issues and risks (Clarkson and Williams, 2020; Cambridge, 2022). GPS and GNSS sensors can provide real-time data on dam displacements, enabling early detection of signs of instability or deformation as shown in Figure 7. Sensors equipped with GPS technology can measure water levels in tailings ponds, helping ensure that the facilities are operating within safe parameters. Advanced positioning systems and sensors can detect subtle changes in the slope of tailings dams or other structures, which could indicate potential instability. Early warning systems leverage positioning data to provide timely alerts to mining personnel and relevant authorities in the event of potential hazards. These systems are particularly critical for preventing dam failures or landslides. After mining operations cease, tailings facilities must be monitored and maintained to prevent long-term environmental damage.

Figure 7 Tailing management using positioning systems (see online version for colours)



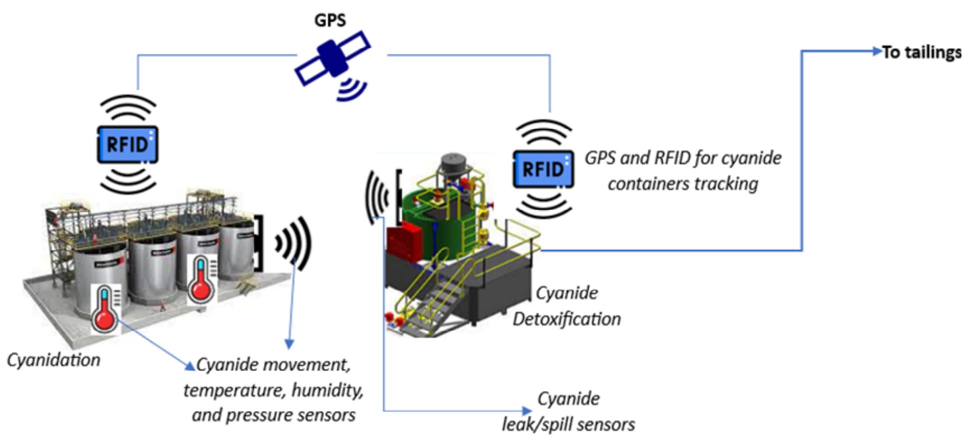
By monitoring tailings facilities and implementing public safety measures, positioning systems protect nearby communities from potential disasters. GIS and remote sensing technologies facilitate predictive modelling of environmental impacts, allowing mining companies to proactively address and mitigate harm to ecosystems and water bodies. GIS technology streamlines the site selection and facility design processes for tailings dams, optimising layouts for safety and efficiency. GPS-based coordination during emergencies ensures efficient evacuation and response efforts, minimising disruption to operations. By reducing accidents and incidents through real-time tracking and safety measures for tailings management, mining companies save on medical costs, legal expenses, and downtime (Adiansyah et al., 2015; Lumbroso et al., 2019; Weyers, 2021). The benefits of positioning systems in tailings management not only enhance safety and environmental protection but also contribute to the long-term sustainability and profitability of mining operations.

4.5 Cyanide management

Cyanide is a critical chemical reagent in the mining industry, primarily used for gold extraction through the process of cyanidation. While it is an efficient and cost-effective method, the handling and management of cyanide pose significant safety and environmental challenges (Bateman, 2010; Das et al., 2023). Accidental cyanide spills or leaks can have catastrophic consequences, both in terms of human health and ecological impact. To mitigate these risks, the mining industry relies on advanced positioning systems integrated with cyanide management practices.

Positioning systems used in cyanide management use various technologies (Barter et al., 2001). GPS and GNSS technologies provide precise location data for tracking cyanide containers, equipment, and personnel involved in cyanide handling and transport. RFID tags and readers are used to monitor and track cyanide containers, ensuring they are properly labelled and accounted for throughout the supply chain. Environmental sensors and telematics systems are employed to monitor cyanide storage conditions, including temperature, humidity, and pressure, to prevent leaks or degradation. Geofencing technology creates virtual boundaries around cyanide storage facilities and transport routes. It triggers alarms and alerts if cyanide containers breach these boundaries.

Figure 8 Cyanide management using positioning systems (see online version for colours)



GPS and RFID are used to track cyanide containers during transportation. Real-time monitoring ensures the secure and accountable movement of cyanide. Sensors placed within cyanide storage areas continuously monitor temperature, humidity, and pressure. Any deviations from safe conditions trigger alarms for immediate action. RFID tagging and GPS tracking provide documentation and proof of compliance with cyanide management regulations as shown in Figure 8. This is invaluable during regulatory audits. In the event of a cyanide leak or spill, GPS data and geofencing technology can pinpoint the exact location, enabling rapid emergency response to contain and mitigate the situation. Positioning systems can track cyanide consumption during gold extraction processes, optimising cyanide usage for efficient gold recovery.

Numerous advantages come from the use of positioning systems in cyanide management. Real-time tracking and monitoring significantly enhance the safety of personnel involved in cyanide handling and transport. Monitoring and rapid response measures prevent cyanide spills and leaks, preserving the environment and minimising ecological harm. Efficient cyanide management reduces resource waste and operational costs, ultimately increasing profitability. Accurate data ensures compliance with cyanide management regulations, preventing legal and financial consequences (Griffiths et al., 2014; Greenwald and Bateman, 2016). Data-driven cyanide usage optimisation enhances gold recovery rates, reducing resource waste and improving operational efficiency.

5 Challenges of positioning systems in the mining industry

The scheduling of equipment, heavy machinery, and other resources, the identification of process constraints, and automatic mitigation techniques are just a few of the future underground mine applications that would depend on precise location. A future mine automation system would also need to integrate well with the various underground mine subsystems to link the process status of the mine processing plant with the transportation and logistics, ore excavation, drilling, and to provide the best overall control of these. Future underground mine applications that would depend on precise location include, for example, fleet management of vehicles and heavy-duty machines in the underground roadways, scheduling of equipment, machines, and other resources, bottleneck identification in the process, and automatic mitigation procedures. The functionality of many other machines in the underground mine, such as trucks, drilling rigs, maintenance vehicles, etc. may be used in conjunction with the autonomous mine loader. To link the process status of the mining concentrator plant, with the transportation and logistics, ore excavation, drilling, and to provide an overall control of these in the best possible way, a future mine automation system would also need to integrate well with the various subsystems in the underground mine.

While personnel tracking systems offer numerous advantages, there are challenges and considerations which need to be addressed. Balancing safety with individual privacy rights is essential. Miners may be concerned about constant tracking, necessitating clear policies and communication. Effective implementation requires integrating tracking systems with existing mine infrastructure, which can be complex and costly. Maintaining tracking systems and providing training to personnel are ongoing tasks that require resources and commitment. Protecting location data from cyber threats is critical, as it can have safety and security implications. Ensuring that tracking systems from different vendors can work together seamlessly can be a challenge in some cases.

For autonomous vehicles to operate with personnel present, it is necessary to position both vehicles and personnel in a secure manner, in real-time, and with great accuracy. All other communication apps must be able to coexist peacefully with the positioning system without interfering with them or making others do so. Extending the range of subsurface communication and maximising the usage of frequency bands for communication and locating. The operating frequency of a wireless system can have a big effect on how well it works. Therefore, it is suggested that the frequency and location positioning system be carefully considered while building a new wireless infrastructure in a tunnel or mine (Ferrer-Coll et al., 2012). Multi-path effects present a serious obstacle for indoor positioning. Signals may experience diffraction, refraction and reflection, which can have a significant impact on their behaviour, due to the nature of the underground environments, which contain metals, waste materials, rocks, walls, and, in some cases, even human bodies.

Slope stability monitoring is indispensable in the mining industry, however, challenges related to its implementation need to be addressed. Implementing monitoring systems can be expensive. Selecting the appropriate technology for a specific mining operation requires careful evaluation. Handling and analysing the vast amount of data generated by monitoring systems necessitates robust data management solutions. Natural factors like vegetation growth and seasonal changes can affect monitoring accuracy. Ensuring precise measurements despite such interference is essential. Effective communication with nearby communities, including explaining the purpose and limitations of monitoring, is vital for building trust. Mining companies must stay updated on evolving slope stability regulations and adjust monitoring systems accordingly.

While subsidence monitoring is critical, there are challenges and considerations which need to be considered. Implementing subsidence monitoring systems can be expensive, and selecting the appropriate technology requires careful consideration. Handling and analysing the vast amount of data generated by subsidence monitoring systems is a complex task that demands robust data management solutions. Natural factors like tree growth and seasonal changes can affect subsidence monitoring systems. Ensuring accurate measurements despite such interference is crucial. Effective communication with nearby communities, including explaining the purpose and limitations of subsidence monitoring, is essential. Mining companies must stay updated on evolving subsidence regulations and adapt monitoring systems accordingly.

Deploying positioning systems, especially for real-time monitoring and early warning systems, can require significant upfront costs for hardware, software, and infrastructure. Ongoing maintenance, software updates, and sensor calibration are necessary to ensure the reliability and accuracy of positioning systems. Mining companies must invest in training and hiring personnel with the necessary skills to operate and maintain positioning systems effectively. Introducing new positioning technologies may require a cultural shift and changes in work processes, which can be met with resistance from existing staff. Adequate training programs are essential to ensure that mining personnel can use positioning systems effectively and interpret the data they provide. Implementing and maintaining positioning systems can be also costly. Careful technology selection is essential to match specific mining operation needs. Handling and analysing the substantial volume of data generated by positioning systems necessitates robust data management solutions. Protecting the privacy and security of data transmitted by positioning systems is paramount, as it may include sensitive information. Mining companies must stay informed about evolving cyanide management regulations and adapt positioning systems accordingly.

6 Future prospects and emerging technologies for mining positioning systems

The future of positioning systems in the mining industry is likely to be shaped by emerging technologies and evolving regulatory frameworks. Artificial intelligence (AI) and machine learning algorithms can be employed to analyse positioning data and identify patterns or anomalies that may indicate potential hazards. AI-driven automation can streamline data analysis and decision-making, enabling faster response to emerging risks. Machine learning models can be developed to assess and predict the risks associated with mining positioning systems data, aiding in proactive risk mitigation. Blockchain technology can be used to secure and verify mining positioning data, ensuring its integrity, and preventing tampering or unauthorised access. Hyperspectral sensors can provide more detailed information about the composition of monitored facilities like tailings and their impact on surrounding environments. LiDAR technology is evolving to provide higher resolution and accuracy, further enhancing slope stability analysis and facility design. It is expected that environmental and safety regulations governing tailings management in the mining industry will continue to evolve, becoming more stringent to prevent disasters and protect ecosystems. Regulatory agencies may require more detailed and frequent reporting of positioning data to demonstrate compliance with safety and environmental standards. International collaboration among mining companies, governments, and organisations can facilitate the exchange of best practices and technologies for the application of positioning systems in the mining industry. Efforts to establish international standards for mining positioning systems can improve consistency and safety across the industry. As technology continues to advance and awareness of environmental and safety concerns grows, positioning systems will play an increasingly vital role in the mining industry, contributing to safer, more sustainable mining practices.

7 Summary and concluding remarks

Any mining operation must prioritise worker safety, but this is especially important in underground mines where there are many potential hazards. Real-time location information and quick emergency response are made possible by positioning systems, which is essential in increasing safety measures. In addition to enhancing safety, this technology has a significant impact on underground mine production and efficiency. Many public, commercial, and wireless networks already require localisation awareness as a key component. However, there is no a single technology or system that consistently outperforms others in terms of availability, efficiency, and accuracy in all real-world circumstances.

Positioning system is transforming the mining industry by improving safety measures and maximising operating effectiveness in mining operations especially in underground mines. The capacity to track and monitor workers and assets in real-time enables mine operators to minimise hazards, enhance emergency response, reorganise workflows, and make the most use of available resources. To ensure worker safety, prevent accidents, and achieve previously unheard-of levels of efficiency in mining operations, this technology has emerged as a crucial instrument. This technology will become more and more important in promoting sustainability, productivity, and safety as the mining industry develops. By embracing this technology, mining companies are better equipped to face the difficulties of the underground environment while protecting their most important resources.

The need to increase worker safety, increase operational effectiveness, and provide new alternatives for sustainable mining serves as the justification for a large portion of the development of core automation system technology. This is generally accomplished by incorporating assistive control, processing, and sensing technologies into the mining process. In this study, the positioning system has been used to show a successful mining operations instance. Both surface and underground mining operations have widely accepted and embraced the usefulness of this technology. This has made it easier for equipment from various suppliers to connect to one another and has given new enabling technologies and systems a platform to be integrated. There will be improvements in system interoperability, process information, deployment cost, and dependability with additional research into the use of new technological systems in the mining industry. Future mining operations will continue to call for innovative, integrated technologies for sensing, processing, and control.

Personnel tracking using positioning systems are a vital tool for enhancing safety in the mining industry. From underground mines to open-pit operations, these systems provide real-time location data, enabling rapid response to emergencies, minimising accidents, and ensuring regulatory compliance. Practical examples demonstrate the diverse applications of this technology in safeguarding miners' lives and well-being. However, the implementation of personnel tracking systems requires careful planning, addressing privacy concerns, and ongoing maintenance. As technology continues to advance, personnel tracking systems will likely become even more sophisticated, further contributing to the safety and sustainability of mining operations. In the end, the primary goal remains unchanged: ensuring that miners return home safely after every shift.

Subsidence monitoring using positioning systems is an indispensable component of responsible mining practices. These systems play a pivotal role in safeguarding the safety of mining personnel, protecting ecosystems, and complying with safety and environmental regulations. Practical examples demonstrate how subsidence monitoring contributes to safety, environmental protection, and economic sustainability. As technology continues to advance, subsidence monitoring systems will become even more precise and efficient, further reducing the impact of mining activities on the environment and surrounding communities. Ultimately, subsidence monitoring exemplifies the mining industry's commitment to balancing resource extraction with safety, environmental responsibility, and community well-being.

Slope stability monitoring assesses the stability of infrastructure located on or near slopes, such as conveyor belts, access roads, and processing plants. Slope stability monitoring helps protect the environment by detecting and mitigating potential hazards like soil erosion and contamination of water bodies. Mining companies use data from monitoring systems to plan and optimise the maintenance of infrastructure on slopes, minimising downtime and costs and enhancing asset management. Ensuring slope stability allows mining operations to proceed without interruptions, preventing financial losses. Monitoring detects and mitigates environmental impacts caused by slope instability, preserving nearby ecosystems.

Positioning systems for slope stability monitoring represent a cornerstone of safe and responsible mining practices. These systems provide real-time, high-precision data that enable early warnings, proactive safety measures, and environmental protection. Practical examples underscore the vital role of monitoring in ensuring the safety of mining personnel, protecting infrastructure, and preserving the environment. As technology continues to advance, slope stability monitoring systems will become even more precise and efficient, further reducing the impact of mining activities on safety and the environment. Ultimately, slope stability monitoring exemplifies the mining industry's commitment to responsible resource extraction, safety, and environmental stewardship.

Positioning systems have emerged as indispensable tools in the mining industry for enhancing safety and environmental protection in tailings management. These systems, including GPS, GNSS, GIS, drones, and others, enable real-time monitoring, early warning systems, facility design, environmental impact assessment, and safety enhancement measures. While positioning systems offer substantial benefits, they also come with challenges related to technology, data management, implementation costs, and workforce adaptation. To address these challenges, mining companies should invest in training, data security, and emerging technologies like AI and blockchain. The future of tailings management in the mining industry holds great promise, with the integration of AI, blockchain, advanced remote sensing, and stricter regulations on the horizon. International collaboration and standardisation efforts will further contribute to safer and more sustainable mining practices. Positioning systems are a vital component of modern tailings management in mining, playing a pivotal role in safeguarding the environment, protecting workers and communities, and ensuring the long-term sustainability of the industry. As technology continues to evolve, the mining sector must adapt and embrace these advancements to meet the challenges of the future.

Positioning systems integrated with cyanide management practices are pivotal in ensuring safety, environmental protection, and regulatory compliance in the mining industry. These systems play a multifaceted role in tracking cyanide transport, monitoring storage conditions, ensuring regulatory compliance, and facilitating emergency responses. As technology continues to advance, positioning systems will become even more sophisticated, further enhancing safety and environmental protection in cyanide usage. Ultimately, cyanide management using positioning systems exemplifies the mining industry's commitment to responsible and sustainable resource extraction, safeguarding human health and preserving the environment.

The goal of the mining companies is to keep workers safe while also boosting production in the mines by removing them from dangerous locations. This paper has examined cutting-edge positioning system that has been used in the mining sector and identified specific mining applications whose success in the development of precise locating systems is crucial. Within this paper, certain crucial benefits, difficulties, and research gaps that need to be filled to expand the application of positioning system beyond what is now possible in the mining industry have been discussed.

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