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(Review Article)

Investigating advanced technologies to enhance worker safety in hazardous mining environments: A Review

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Abstract

The mining industry represents a critical and high-risk engineering field characterized by complex occupational health and safety challenges. With the advancement of technology, various approaches can be explored to help reduce the risk encountered by workers in this area. The application of Artificial Intelligence (AI), Automation, Internet of Things (IoT), Advanced Sensors, and Virtual Reality is gradually reshaping safety in mining operations by offering a more efficient approach to identifying and mitigating risks. This paper reviews unique research and applications of Artificial Intelligence (AI), Automation, Internet of Things (IoT), Advanced Sensors, and Virtual Reality to address safety issues in the mining sector. The mining industry is undergoing a technological revolution driven by AI, IoT, advanced sensors, and VR, aimed at dramatically improving workplace safety and operational efficiency. These innovative technologies promise to transform traditional risk management by shifting from human-centric to intelligent, predictive system architectures.

Keywords: Artificial Intelligence; Technology; virtual reality; mine rescue

1. Introduction

The mining industry is characterized by high health risks, necessitating robust occupational health and safety management (OHSM) to protect workers and achieve business goals. [1] Whilst mining remains one of the greatest achievements of industrial engineering, the industry remains complex and full of dangers. Mining is an industry focused on human skill and mechanical precision in a high-risk environment with a historical past in terms of the highest risks of fatality and injury [2].

According to the USA Bureau of Labor Statistics, in the mining and extraction industry, fatal injuries increased by 21.8% in the last decade [3]. In contrast, in the overall industry, the number of fatalities rose from 78 in 2020 to 95 in 2021. This is likely due to restricted operations caused by the COVID-19 outbreak. The increase observed in 2021 indicates that as operations in the industrial sector resumed, so did the dangers of this risky industry. The total number of fatalities of workers in the mining industry in the United States in 2023 was 40, which is a decrease of approximately 44 % from the total recorded in 2020-2021. This decline is likely due to the implementation of safety and technological improvements in mining activities.

Over the past decades, the mining sector has seen an increase in the use of technology to improve safety in operations. With the emergence of automation, Artificial Intelligence, virtual reality, and robotics, carrying out certain high-risk activities has significantly reduced the occurrence of accidents.

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This critical review aims to investigate and analyze the most advanced technological interventions designed to improve worker safety in hazardous mining environments, exploring their potential to fundamentally reshape occupational health and safety management approaches.

2. Overview of Technological Innovations and Data-Driven Approaches in Mining Safety

In a comprehensive overview of technological advancements in mining safety, valuable information of emerging tools and techniques designed to mitigate risks in one of the world's most hazardous industries were discussed. Kumar et al., [4] in his review effectively demonstrates the critical role of automation, robotics, communication technologies, and geographic information systems (GIS) in transforming mine safety practices. For instance, in similar research, the systematic exploration of technologies such as autonomous mining systems, rescue robots like Groundhog and Ferret, and advanced communication networks illustrated the significant potential for reducing human exposure to dangerous mining environments [5].

Other research presents an innovative approach to safety management in coal mining by applying data mining techniques to accident data through an evidence-based safety (EBS) framework. The study's strength lies in its attempt to move beyond subjective expert judgment by using computational methods like term frequency-inverse document (TF-IDF), TextRank and Latent Dirichlet Allocation to extract meaningful safety insights from historical accident data. The authors propose a potentially transformative methodology for converting raw accident data into actionable safety evidence. The research primary contribution is demonstrating the potential of data-driven approaches in safety management, with a framework for more systematic and evidence-based safety decision-making in high-risk industries like coal mining [6]. To outline the importance of experimental research, various models including, Burgers Model, have been developed to address the problem of understanding how gas presence affects the creep behavior of coal, which is critical for preventing coal and gas outburst accidents in mining [7].

2.1. The Role of Artificial Intelligence in Mine Safety

By leveraging historical incident data and real-time monitoring, Artificial Intelligence has the potential to proactively prevent workplace accidents [8]. For example, blasting is a common operational practice in the mining sector that has many hazards. In a recent study, an artificial intelligence model tagged: Brain Inspired Emotional Neural Network (BI-ENN) was used for predicting air overpressure from blasting operations, the model leverages neurophysiological principles to enhance prediction accuracy and efficiency during blasting. The results demonstrate that BI-ENN outperforms other methods in statistical accuracy, making it a robust tool for monitoring and managing air overpressure in mining environments [9]. Similarly, data from 230 blast operations were analyzed in a Scientific study using Artificial Intelligence techniques, artificial neural networks, and fuzzy logic to predict fly rock distances during blasting operations. The fuzzy logic demonstrated high performance in prediction accuracy, thus highlighting the effectiveness of AI in enhancing safety and reducing hazards in mining operations [10]. Other investigations have revealed performance at 91.4% accuracy when artificial intelligence (AI) models, enhanced with metaheuristic algorithms, were used to predict blast-induced ground vibration intensity in open-pit mines [11]. The success of this research, therefore, emphasizes the effectiveness of AI in ensuring operational safety and minimizing hazards.

Artificial intelligence (AI)-based approaches have also been used to assess the stability of mine rock slopes by introducing an AI model that integrates algorithms such as genetic, neural network, and ant colony optimization to address challenges in the industry. However, the quality of the approaches developed heavily relies on the quality and size of training data, which can be a limitation [12]. The paper "Using Artificial Intelligence in Mining Excavators: Automating Routine Operational Decisions" critically explores the integration of AI-driven systems to enhance mining excavator operations, focusing on safety, efficiency, and decision-making. The authors detail the development of a multi-frame object detection model using you only look once (YOLO) and long short-term memory (LSTM) architectures, enabling capabilities like missing tooth detection, payload monitoring, and fragmentation analysis. The solutions demonstrate high accuracy and operational improvements and the potential of AI for transformative impact in mining thus calling for broader adoption and integration into existing systems for maximum effectiveness [13]. Other models, such as the Gradient Boosting Regression Tree (GBRT) algorithm demonstrated high accuracy and reliability in predicting landslide risks in open pit mine dumps, especially under heavy rainfall. This offers critical insights for disaster prevention in mining operations [14].

The integration of Artificial Intelligence (AI) in mining industries can improve operational efficiency, safety, and environmental sustainability while addressing challenges associated with conventional mining methods [15]. Despite the promising results of various AI applications in mining safety, the effectiveness of these models is fundamentally constrained by the quality and quantity of training data.

2.2. The Role of Automation in Mine Safety

Over the years, there has been a development of autonomous haulage systems in mining, driven by economic pressures and technological advancements. The primary focus of these developments is to improve productivity and worker safety. With a safety-centric approach to unmanned dump trucks, the complex transformation of operational management that shifts safety responsibilities from human operators to system architecture is needed. Apart from safety, the mining industry's trend towards automation is also motivated by worker shortages, rising personnel costs, and emerging technologies like Internet of Things(IoT) and AI [16]. Automated Safety Control System and Monitoring (ASUiM) for managing geodynamic risks have also been explored where they offer reliable information for prediction and prevention of rock-tectonic shocks, enhance mining enterprise safety, and provide early warning services signals [9]. Additionally, innovative robotics solutions like an autonomous vehicle, Unmanned Aerial Vehicles (UAV)-based heap leach pile inspection system, and an enhanced vision system for vehicle teleoperation in addressing mine challenges are currently being explored in varying research [17]. Modern control systems can significantly improve safety, efficiency, and operational reliability in mining operations by adopting advanced distributed control and automation systems for the mining industry, focusing on self-powered sensors and intelligent communication networks. Flexible, reliable, and intrinsically safe technological solutions can be created to operate in challenging mining environments, particularly those with risks of methane and coal dust explosions [18].

Advanced electronically controlled automation systems for underground drilling rigs in coal mines are often important as mining processes become even more sophisticated. By focusing on enhancing safety and reducing manual operations technologies like remote control, parameter monitoring, and automatic drilling and pull-out capabilities can be adopted. Research by Dong et. al [19] created a system consisting of a vehicle-mounted terminal and a mobile terminal, which integrates functions such as visual-range remote control, working condition logic judgment, and safety interlocking. The system demonstrated reliability, with successful underground field applications showing timely response, stable operation, and improved personnel safety in coal mining environments.

Ralston et. al [20] explored the development of longwall automation technology in underground coal mining, outlining their wider adoption to improve safety, productivity, and efficiency in the industry. Though key challenges include enhancing sensing capabilities, developing robust system architectures, improving autonomous operation, and addressing human-machine interaction, specific focus areas like proximity detection and remote operating centers were identified in this approach, highlighting the potential of technological integration to transform underground coal mining in the long run.

While automation in mining shows significant promise for improving safety, productivity, and operational efficiency through technologies like autonomous haulage systems, unmanned aerial vehicles, and advanced control systems, the approach is constrained by challenges such as developing robust system architectures, enhancing sensing capabilities, and effectively managing human-machine interactions.

2.3. The Role of the Internet of Things (IoT) in Mine Safety

The internet of things (IoT) is also one aspect of technology that is transforming the outlook of devices used in the mining industry. Devices are now being upgraded with network connectivity, allowing them to communicate with each other and the cloud. Popularly termed as “smart objects,” the idea around IoT is to create devices that can report on themselves and communicate in real time.

It has been identified that various challenges and opportunities are associated with health sensing technologies in underground mining environments, emphasizing the need for reliable and robust systems to monitor worker health and safety. Usually, extreme conditions like high temperatures, humidity, and limited connectivity are key obstacles to deploying effective sensing solutions. Innovations in wearable sensors, machine learning, and network integration devices can enhance real-time health monitoring and ensure safety in these demanding industrial settings [21]. Smart wearable devices integrating IoT-based health monitoring for coal miners have been designed to detect hazardous gases, monitor vitals, and alert both miners and control rooms during emergencies [22]. Not all solutions of wearing devices provide live video monitoring and advanced predictive capabilities; as such, there may be limitations in distributing live feeds.

A proposed safety system for coal mining has been able to implement advanced technologies in helmets to mitigate industry risks. Safety helmets are integrated with IoT and AI sensors which continuously monitor environmental and physiological conditions, tracking toxic gases, temperature, humidity, and miners' vital signs. The system has been designed for real-time communication and emergency response through features like a panic button, gesture recognition, and direct wireless alerts to a central control center [23]. Research on advanced computer vision systems to enhance Personal Protective Equipment (PPE) compliance detection using pose estimation and innovative object detection models indicates a huge prospect in ensuring compliance with safety protocol by mine workers. This innovation is designed to successfully identify and verify the usage of PPE in mining environments, demonstrating significant potential for improving compliance and eventually reducing occupational hazards in challenging underground mining environments [24]. Despite promising results, the research acknowledges existing challenges such as low-light conditions and detection difficulties caused by equipment like gloves, pointing to critical areas for future model refinement and broader applicability across diverse mining settings.

This innovative approach of IoT aims to significantly enhance worker safety by providing a more responsive and comprehensive monitoring solution compared to traditional safety equipment.

While IoT technologies in mining show immense potential for enhancing worker safety through smart wearable devices, intelligent helmets, and advanced monitoring systems that can detect environmental hazards and track physiological conditions, the approach faces significant challenges including limited connectivity in extreme underground conditions, difficulties in live video monitoring, and detection complexities in low-light environments.

2.3.1. Sensors

Various Physical Environmental Challenges, such as high temperature, low oxygen levels, extreme humidity, the presence of pervasive dust, and especially the emission of harmful fumes, arise during underground mining; hence, there is a critical need for advanced monitoring systems to protect miners in such dangerous subterranean environments. There is paramount importance of real-time tracking and environmental monitoring in underground mines to detect, monitor, and prevent incidents that may occur because of the working environment [25]. In a study to identify the enumerate the operating principle, working procedure, and application of different types of sensors for monitoring toxic and flammable gases in hazardous areas it was identified that an ideal sensor would possess: (i) high sensitivity, dynamic range, selectivity and stability; (ii) low detection limit; (iii) good linearity; (iv) small hysteresis and response time; and (v) long life cycle [4]. However, the analysis demonstrates that no single sensor type can comprehensively detect all hazardous gases, with each approach.

Table 1 Comparison of various gas detection techniques [4].

Sensor	Advantages	Disadvantages
Catalytic	Simple, robust, and inexpensive.	Sensor poisoning, sensor inhibitors, and sensor cracking
Infrared	Immune to poisons and contamination, fail-safe operation, no routine calibration is required, and ability to operate in continuous presence of gas.	Flammability detection is only in %LEL range, high to medium power consumption, and the gas must be infrared active.
Electrochemical	Reliable, fast response, low power, measures toxic gases in relatively low concentration, and wide range of gases can be detected	Limited to operate at low ambient temperature and narrow pressure range, unsuitable for use in dry atmosphere and not fail-safe.
Semiconductor (solid state)	Robust, long operating life, wide operating temperature range, detect wide range of gases.	Commonly poor selectivity causing 'false' alarm, high power consumption and response drift problem.
Fiber optic (clad modified)	High sensitivity, short response time and operate at room-temperature.	Not stable for long time, irreversibility, and low selectivity.
Laser	No interference from other gases, high speed, high selectivity, low maintenance and operating cost, and self-calibration.	Only one gas can be measured with each instrument; heavy dust, steam or fog blocks laser beam.

Flame ionization detector	Best for CHC compounds.	Not used in explosive areas, destroy the sample, responds poorly to halogenated hydrocarbons, and non-specific response.
Photo Ionization	Good method for organic compound detection at low level.	Non-specific response, and responds only to ionizable gases.
Thermal Conductivity	General applicability, large linear range, simplicity and non-destructive.	Low sensitivity

In other research, correlation of vital signs with saliva pH was successfully used to estimate fatigue. This result represents a promising advancement in occupational health tracking, potentially overcoming previous challenges in accurately measuring miners' physiological stress levels [26]. However, the study's credibility could be enhanced by providing more detailed validation data, discussing potential individual variability in the fatigue estimation model, and exploring the long-term reliability and adaptability of the proposed technology across different mining environments. In another research, an IoT-based "Smart Safety Jacket" equipped with multiple sensors, including temperature, humidity, ultrasonic, and gas sensors, was developed to monitor workers' safety in real-time. It works by transmitting data through Wi-Fi to a remote monitoring system, enabling instant detection and response to potential risks [27].

While sensors in underground mining represent a critical technological solution for detecting and monitoring environmental hazards, workplace risks, and worker physiological conditions, the research reveals significant challenges, including the inability of any single sensor type to comprehensively detect all hazardous gases, the need for sensors with high sensitivity, low detection limits, and long life cycles, and the requirement for more robust validation of innovative monitoring technologies like saliva pH fatigue estimation. The research collectively underscores the paramount importance of advanced, multi-sensor monitoring systems that can provide real-time tracking in extreme underground environments characterized by high temperatures, low oxygen levels, extreme humidity, pervasive dust, and harmful fumes, with technologies like IoT-based "Smart Safety Jackets" offering promising approaches to enhance worker safety through comprehensive, instantaneous risk detection and response capabilities.

2.4. Virtual Reality

Virtual Reality (VR) technology is increasingly being recognized as a transformative tool in high-risk industry processes. The application of virtual reality technology in industries with high accident rates, such as mining and construction, contributes to sustainability by enhancing occupational health and safety (OHS) practices [28]. For instance, VR-based training significantly reduces learning time, error rates, and increases knowledge retention, which contributes to reducing workplace accidents and improving workforce productivity [29]. A paper investigated the process of mine rescuers' safety training with immersive virtual reality. Here, they used the Structural Equation Modelling Approach as a comprehensive evaluation of immersive virtual reality (VR) tool for training mine rescue brigades. However, the study's findings are somewhat constrained by the single VR scenario tested and lack of validation against broader datasets [30].

While Virtual Reality (VR) technology shows immense potential for enhancing safety training in high-risk industries like mining by reducing learning time and error rates, its current limitations include the need for more comprehensive validation across diverse scenarios and broader datasets to fully establish its effectiveness in improving occupational health and safety practices.

3. Conclusion

The research collectively demonstrates that AI has significant potential to revolutionize mining operations by enhancing safety, efficiency, and predictive capabilities, with multiple studies showcasing high-accuracy models for tasks like ground vibration prediction, fly rock distance estimation, and landslide risk assessment, ultimately suggesting that broader adoption and integration of AI technologies could transform the mining industry's approach to operational risk management. Additionally, the future of mining safety lies in flexible, intelligent technological solutions that can operate in challenging environments, with a critical need to shift safety responsibilities from human operators to sophisticated system architectures that leverage emerging technologies like IoT, AI, and advanced robotics. IoT and AI integration in mining safety represents a transformative approach to worker protection, with innovations like real-time health monitoring, emergency response systems, and PPE compliance detection offering promising solutions. The research also highlights the importance of advanced, multi-sensor monitoring systems that can provide real-time tracking in extreme underground environments characterized and the adoption of Virtual Reality (VR) technology, which shows immense potential for enhancing safety training in high-risk industries. Continued refinement of technologies is necessary to address current limitations and ensure broader applicability across diverse mining settings.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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