**Introduction**

In the mining industry, the safety and health of miners has always been one of the most important concerns. The mine environment is complex and changeable, and there are many potential dangerous factors, such as toxic gas leakage, landslides, mechanical failures, and extreme temperatures, which pose a serious threat to the life safety of miners (Bo et al., 2014). Although traditional safety protection measures and monitoring methods have improved the working conditions of miners to a certain extent, they are still insufficient to cope with sudden emergencies and health risks. With the advancement of technology, the application of smart devices has provided new possibilities for improving the safety and health monitoring of miners (Dempsey et al., 2018).

This paper reviews the existing relevant literature and discusses the current development status of intelligent safety equipment, the application of relevant sensor technologies in mining, and the latest progress in data transmission and processing, in order to provide a theoretical basis for the development of intelligent safety helmets integrated with advanced sensors. As an advanced device that integrates multiple sensors, the smart safety helmet can monitor miners' vital signs and environmental risks in real time, provide timely warnings and data support, and thus greatly improve the safety of mine work. Therefore, this project aims to develop a smart safety helmet that integrates vital signs sensors, toxic gas sensors and acceleration sensors to comprehensively monitor the miners' heart rate, body temperature, toxic gas concentration in the environment and head impact. Through wireless communication technology, the data collected by these sensors will be transmitted to the data repository in real time, facilitating real-time monitoring and rapid response by security personnel.

This study will not only help reduce the occurrence of mine accidents and protect the lives of miners, but will also promote the improvement of mining safety standards and technological innovation. In this context, exploring the application of smart safety helmets in mine environments has important practical significance and academic value.

**Research status/literature analysis**

Traditional mine safety protection measures and monitoring systems mainly focus on macro-environment monitoring, that is, using wired monitoring systems to monitor the safety of the entire mine or a specific area. This macro-monitoring can provide a certain degree of security, and the research of Muduli et al. (2018) shows that with the development of Internet of Things technology, the efficiency of mine safety monitoring can be improved by combining wireless sensor networks with existing wired monitoring systems.However, Dempsey (2018) also pointed out that the current mine safety system lacks active detection and real-time monitoring of the miners' individual surrounding environment. Although some mines will equip miners with portable hazardous gas detectors, these devices are usually unable to transmit data and cannot be used to monitor the miners' working environment data in real time. Most importantly, the traditional monitoring system cannot monitor the vital signs of each miner (such as heart rate and body temperature). In summary, miners currently need a device that can detect vital signs and individual environment.

In order to make up for the shortcomings of traditional safety systems, Mardonova and Choi (2018) believe that the most mainstream and effective method is to equip miners with smart wearable devices. Their research reviewed the application and deployment of wearable device technology in the mining industry, and evaluated various types of wearable devices such as smart watches. Their research believes that the deployment of advanced sensor technology in the form of wearable devices can help improve the safety of miners' working environment. Adjiski (2019)'s research results are the same as Mardonova's. They explored the possibility of installing sensors on conventional personal protective equipment to transform them into smart wearable devices, and recognized the application prospects of smart wearable devices in the mining industry. Their research also explored the possibility of connecting multiple wearable devices in wireless or Bluetooth form to form a wearable safety management system. These devices integrate sensors, wireless communications and data analysis technologies to monitor miners' health status and environmental parameters in real time, and provide timely warnings and data support.

Based on the above analysis of the literature and combined with Svertoka's (2021) classification research on wearable devices in industrial production scenarios, there are currently two main types of wearable smart devices in the mining industry. One is a wearable wristband or smart watch. Wearable wristbands are currently the most widely used smart wearable devices, and have mature technical accumulation in their applications in medical and health testing (Hahnen et al., 2020). There are also research precedents in the mining industry for using wearable wristbands to monitor miners' vital signs. Sarkar (2020) designed a wearable wristband and conducted extensive experiments in underground mines. The equipment used BME680 and GMR sensors to detect miners' vital signs data and successfully obtained human body data such as miners' heart rate, respiratory rate, and blood pressure. Another is to improve the equipment that miners often wear. The personal protective equipment that miners wear daily, such as helmets and protective clothing, is an ideal platform for intelligent improvement. For example, a study improved the work uniforms of miners (Abro et al., 2018), installed devices such as DHT 11 humidity sensors and pulse sensors on the jackets worn by miners, and designed data transmission and location detection functions. On the basis of the original protective functions of the jackets, more intelligent functions were added to improve the safety and health monitoring level of miners.

Taking into account environmental adaptability, sensor integration, data transmission stability, safety and emergency response, etc., it is better to improve the personal protective equipment that miners wear daily than to use wearable wristbands directly. Therefore, this project finally chose to make a smart helmet with integrated sensors. The main reasons are as follows: Sensor integration: Compared with wristbands, helmets have enough space to integrate multiple sensors, and can simultaneously deploy multiple functions such as heart rate, body temperature, toxic gases, acceleration, etc., providing comprehensive monitoring functions (Mardonova & Choi, 2018). Safety training and usage habits: In the mining safety supervision regulations of most countries, such as China's "Mine Safety Law" and the United States' "Mine Act", it is clearly required to wear a helmet. Therefore, the intelligent helmet can be seamlessly connected with the miners' existing safety training and operating habits, reducing the need for additional training. Miners are already accustomed to wearing it, and the newly added intelligent functions will not have much impact on their daily operations.

Of course, there are studies (Adjiski et al., 2019) that choose to equip multiple smart devices (safety helmets, safety glasses, and smart watches) at the same time to detect environmental and vital signs data, and transmit the data to a smart device via Bluetooth. The advantage of this is that there is no need to consider the integration of a single device and the sensor space. However, another report from Ranjan (2019) also pointed out that the deployment of smart devices in mines needs to face complex and changeable geographical electromagnetic environments, and wireless and Bluetooth transmissions are easily interfered and affected. Therefore, too many device connections and data transmissions are not a good choice.

In underground mine environments, smart helmets transmit collected data to data repositories through wireless communication technology. This data is essential for real-time monitoring and ensuring the safety of miners. In terms of data transmission, the three commonly used wireless systems are Bluetooth, Wi-Fi, and ZigBee, each with its own advantages and disadvantages. This paper will compare ZigBee with WiFi and Bluetooth, combining existing literature and research (Soomro & Jilani, 2020) (Moridi et al., 2018) (Ikeda et al., 2021), focusing on analyzing the advantages and disadvantages of the three wireless systems in underground mine environments.

1. Power consumption comparison: ZigBee is designed for low-power applications, and devices can work for a long time without frequent battery replacement. This is especially important for smart helmets worn by miners, reducing the frequency of maintenance and battery replacement. And ZigBee devices can enter sleep mode to save power when there is no need to transmit data. WiFi devices typically consume more power to stay connected and transmit data, especially when data is being transmitted continuously. This is a significant disadvantage for mining equipment that needs to work for a long time and is difficult to rely on battery power for long periods of time. Bluetooth power consumption is lower than WiFi but higher than ZigBee, and is suitable for medium-frequency data transmission. Bluetooth's power consumption advantage is mainly reflected in short-distance transmission, which is suitable for portable devices.
2. 2. Network topology and coverage: ZigBee supports star, tree and mesh topologies, and can be flexibly deployed according to the actual environment of the mine. Mesh networks are particularly suitable for complex geographical environments such as mines, ensuring that data can be reliably transmitted through multiple nodes. WiFi usually uses a star topology, which requires multiple access points to cover a large area. In a mine environment, this topology may be limited by terrain and obstacles. The signal has a limited transmission distance in an underground environment and is easily interfered by terrain and building structures, requiring more access points to achieve full coverage. Bluetooth mainly supports point-to-point and star topologies, which are suitable for short-distance device connections. However, Bluetooth has a short transmission distance, which is suitable for data transmission between short-distance devices and is not suitable for large-scale mine environments.
3. Data transmission rate: ZigBee was originally designed to serve low data rate applications, with a typical rate of 20-250 kbps. Although the rate is low, it is sufficient to meet the needs of most sensor data transmission, especially vital signs and environmental monitoring data. Therefore, ZigBee's low rate is more suitable for frequent transmission of small data packets, reducing transmission delays and energy consumption. WiFi supports a higher data transmission rate, and has obvious advantages for applications that need to transmit large amounts of data. However, for this project, the high-speed design of WiFi is less efficient when processing frequent small data packets, which may lead to unnecessary increase in energy consumption. The data rate of Bluetooth is between ZigBee and WiFi, which is suitable for medium-sized data transmission. The Bluetooth Low Energy (BLE) version supports lower rates and power consumption.
4. Interference and reliability: All three wireless systems can operate in the 2.4 GHz frequency band, but ZigBee's protocol design makes it more resistant to interference and suitable for use in industrial environments. Bluetooth and WiFi are easily interfered by other WiFi devices and electronic devices, especially in complex underground mine environments with high usage frequencies.

Comprehensive comparison shows that ZigBee has significant advantages over WiFi and Bluetooth in terms of power consumption, network topology flexibility, coverage, anti-interference capability and reliability, and is particularly suitable for use in underground mine environments. Although WiFi performs well in terms of data transmission rates, its shortcomings such as high power consumption, limited coverage, and susceptibility to interference limit its application as the primary data transmission method in mines. Although Bluetooth is suitable for short-range low-power applications, it is not as good as ZigBee in terms of coverage and anti-interference capabilities. Through its low power consumption and high reliability characteristics, ZigBee can better meet the needs of miners' smart helmets for data transmission to data storage libraries, providing a more stable and efficient solution.

**Conclusion**

This paper reviews the existing literature and analyzes the current status and main technological progress of intelligent safety equipment in mines. The study shows that traditional mine safety protection measures and monitoring methods mainly focus on macro-environment monitoring, lacking active detection and real-time monitoring of the surrounding environment of individual miners. Smart wearable devices can make up for this shortcoming by integrating advanced sensor technology and wireless communication technology. In particular, they have obvious advantages in improving the personal protective equipment (such as helmets) that miners wear daily. The smart helmet has built-in sensors that can monitor multiple vital signs and environmental parameters at the same time, thereby providing timely early warning and data support, significantly improving the safety and health monitoring level of mine work. In addition, the smart helmet seamlessly integrates with miners' existing safety training and operating habits, reducing the need for additional training and having high user acceptance and ease of use. In summary, smart safety helmets have important application value in underground mine environments. Smart safety helmets provide an effective solution to protect the lives and health of miners by integrating multiple sensors and adopting low-power wireless communication technologies such as ZigBee.