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Review

Review of Wearable Device Technology and Its Applications to the Mining Industry

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Abstract: This paper reviews current trends in wearable device technology, and provides an overview of its prevalent and potential deployments in the mining industry. This review includes the classification of wearable devices with some examples of their utilization in various industrial fields as well as the features of sensors used in wearable devices. Existing applications of wearable device technology to the mining industry are reviewed. In addition, a wearable safety management system for miners and other possible applications are proposed. The findings of this review show that by introducing wearable device technology to mining sites, the safety of mining operations can be enhanced. Therefore, wearable devices should be further used in the mining industry.

Keywords: mining; wearable technology; smart helmet; smart eyewear; occupational health; sensor technology

1. Introduction

A considerable amount of attention has been paid to wearable (electronic) devices since Google Inc. recently launched head-mounted displays [1]. Wearable devices have managed to garner a position of significance in the consumer electronics market in a short time, and are considered a new means of addressing the needs of many industries. For example, the construction industry has studied the use of wearable devices in the workplace for health and safety management by proximity detection and physiological monitoring of construction workers [2]. The logistics industry has begun using wearable barcode scanner gloves called ProGloves to simplify work that does not involve the use of hands [3], and some insurance companies are promoting the use of wearable devices to encourage healthier eating habits and improve corporate wellness among workers [4]. Furthermore, several wearable devices, such as fitness trackers, are used by medical professionals to acquire physiological, behavioral, and contextual data for the diagnosis, treatment, and management of chronic diseases [5–7]. Although many studies are underway to determine how these devices can be best adapted to different industries, it is expected that the applications of wearable device technology will rapidly expand in the near future [8].

In recent years, some applications of wearable devices have been reported in the mining industry to support production process control in hard rock mines [9], health and safety management in coal mines [10–12], and environmental quality monitoring in industrial mineral mines [13]. For example, a smart safety helmet with methane and carbon monoxide gas sensors was developed to alert underground coal mine workers when the concentration of harmful gases exceeded a given limit [10]. Because many accidents in underground coal mines are caused by gas leakages, the smart safety helmet shows how wearable device technology can be adapted to the mining industry for health and safety management. However, no study to date has summarized cases where wearable devices have been used in mining, so that their current and potential uses can be understood easily.

The purpose of this study is to review trends in wearable device technology and its applications to the mining industry. This paper presents a classification of wearable devices and features of sensors that can be attached to them. Current cases of the use of wearable devices in mining sites are reported, and possible applications including a wearable safety management system for miners are proposed.

2. Classification of Wearable Devices

Wearable devices can be classified based on their function, appearance, proximity to the human body, and other parameters [14,15]. This study classifies them according to their functional properties and capabilities to further explain their applications to industrial sectors, as shown in Table 1.

Table 1. Classification of wearable technologies, along with their properties, capabilities, and sectors of application.

Type	Properties	Capabilities	Applications
Smartwatch	-low operating power -user-friendly interface with both touch and voice commands	-displays specific information -payment -fitness/activity tracking -communication -navigation	-business, administration -marketing, insurance -professional sport, training -education -infotainment
Smart eyewear	-controlled by touching the screen, head movement, voice command, and hand shake -low operating power -sends sound directly to the ear	-visualization -language interpretation -communication -task coordination	-surgery -aerospace and defense -logistics -education -infotainment
Fitness tracker	-high accuracy -waterproof -lightweight -wireless communication	-physiological wellness -navigation -fitness/activity tracking -heart rate monitor	-fitness -healthcare -professional sport -outdoor/indoor sport
Smart clothing	-no visual interaction with user via display or screen -data are obtained by body sensors and actuators	-heart rate, daily activities, temperature, and body position tracking -heating or cooling the body automatic payment	-professional sport-fitness -medicine -military -logistics
Wearable camera	-making first-person capture attachable on clothes or body -smaller dimensions -night vision	-captures real-time first-person photos and videos -live streaming -fitness/activity tracking	-defense -fitness -industry -education
Wearable medical device	-pain management -physiological tracking -glucose monitoring -sleep monitoring -brain activity monitoring	-cardiovascular diseases -physiological disorders -chronic diseases; diabetes -surgery -neuroscience -dermatology -rehabilitation	-fitness -cardiovascular medicine -psychiatry -surgery -oncology -dermatology -respirology

2.1. *Smartwatch*

Smartwatches are computerized devices or small computers intended to be worn on the wrist, and have expanded functionality that is often related to communication. Most current smartwatch models are based on a mobile operating system. Some operate as smartphone-paired devices and provide an additional screen with which to inform the wearer of new notifications, such as messages received, calls, or calendar reminders. Manufacturers continue to develop their products and add features, such as waterproof frames, global positioning system (GPS) navigation systems, and fitness/health tracking features [16]. With the addition of reliable, sensitive inertial sensors on them, smartwatches can now be used to capture and analyze hand gestures, such as smoking or other activities [17].

2.2. Smart Eyewear

Another category of wearable devices, smart glasses or smart goggles are used for various applications in optical head-mounted displays (OHMDs), heads-up displays (HUDs), Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and smart contact lenses. Despite differences in functionality and design, all smart glasses can be divided into two groups: those paired with a smartphone, needed to see images on the smartphone screen, or separate ones, which require a wired connection with a source device [16]. The displays of smart glasses can be monocular if the information is displayed for a single eye or binocular if an image is displayed for both.

2.3. Fitness Tracker

Fitness trackers, also known as activity trackers, are typically worn on the wrist, chest, or ears, and are designed to monitor and track outdoor sport activities and measure fitness-related metrics, such as the speed and distance of running, exhalation, pulse rate, and sleeping habits [18]. Some studies in [19–21] examined a number of activity trackers and measured their accuracy and reliability at counting steps. The conclusion was that some trackers perform well indoors and provide valid results, whereas others are more suitable for outdoor activities. Researchers suggest that trackers provide health empowerment for users [22], and their adoption can encourage overweight children to exercise more [23]. Professional soccer teams in Europe and the United States have used the activity tracker miCoach, manufactured by Adidas to quantify the physical performance of players [24].

2.4. Smart Clothing

Although aspects of smart clothing are similar to other types of wearable devices that monitor the physical condition of the wearer, they include a broad list of wearables, ranging from sportswear and consumer sports apparel (smart shirts and body suits) to chest straps, medical apparel, work wear monitoring apparel, military apparel, and e-textiles [25]. Smart clothing consists of a range of articles, although it is typically in the form of shirts, socks, yoga pants, shoes, bow ties with secret cameras, helmets, and caps with a wide range of sensors and features. Wearable smart biometric devices have attracted the attention of professional sports leaders in golf, soccer, athletics, racing, basketball, and baseball, and teams and athletes are already benefitting from the application of wearables to monitor the physical condition of players while training, to reduce the number of injuries and enhance team performance [26]. Smart clothing has the potential to be exceedingly beneficial for firefighters [27], at construction sites [28,29], and for transportation [30,31].

2.5. Wearable Camera

In contrast to conventional cameras, the user-friendly design, mobility, and flexibility of wearable cameras have attracted significant interest from consumers. The appeal of these cameras is that they are well-suited for creating first-person videos and photos in real time. Two major types of wearable cameras are used: small cameras that can be attached to either the body or clothes, or can even be worn in the ear, and larger cameras with mounting attachments to affix to caps or helmets [16]. Some researchers have shown the significance of wearable cameras for fall detection [32] and monitoring ecological environments [33].

2.6. Wearable Medical Device

A wearable medical device typically consists of one or more biosensors used to monitor a variety of physiological data to prevent disease, provide early diagnoses, and facilitate treatment and home rehabilitation [34,35]. Digital healthcare wearable devices are often grouped together with other wearables, such as activity monitors, smartwatches, smart clothing, and patches, and are all intended to help gather important data concerning the health of the patient using non-invasive sensors installed on the device.

3. Features of Sensors Used in Wearable Devices

Various types of sensors are used in wearable devices depending on the intended application. Many manufacturers around the world produce such sensors for individuals or professional developers. Because sensors are important components of wearable devices best-suited to the mining industry, this paper reviews the features of sensors by dividing them into four major groups: environmental sensors, biosensors, location tracking sensors, and other sensors.

3.1. Environmental Sensors

Environmental sensors are used for measuring, monitoring, and recording environmental conditions or properties [36], such as barometric pressure, relative humidity, luminosity, temperature, dust, and water level. Light sensors (see Figure 1a) that can be used to detect light are widespread in scientific applications and everyday consumer products, such as motion light sensors, ambient light sensors, outside lights, security lights, and traffic light sensors. Sound sensors or microphones (see Figure 1b) are employed to determine the sound intensity of an environment. They come in multiple forms including condensers, ribbons, carbon, and dynamic microphones [37]. The most common type consists of dynamic microphones that measure noise levels in decibels at frequencies to which humans are sensitive.

A humidity sensor (see Figure 1c) measures the relative humidity in the air for use in moisture and temperature measurements [38]. These are sometimes referred to as humidity/dew sensors, and can be found in heating, ventilation, or air conditioning systems in buildings. Flame sensors (see Figure 1d) are used to detect open flames or fire, and are more sensitive and accurate than commonly used smoke or heat detectors. Fume sensors (see Figure 1e) perform a similar function in detecting smoke, alcohol, and other harmful airborne gases.

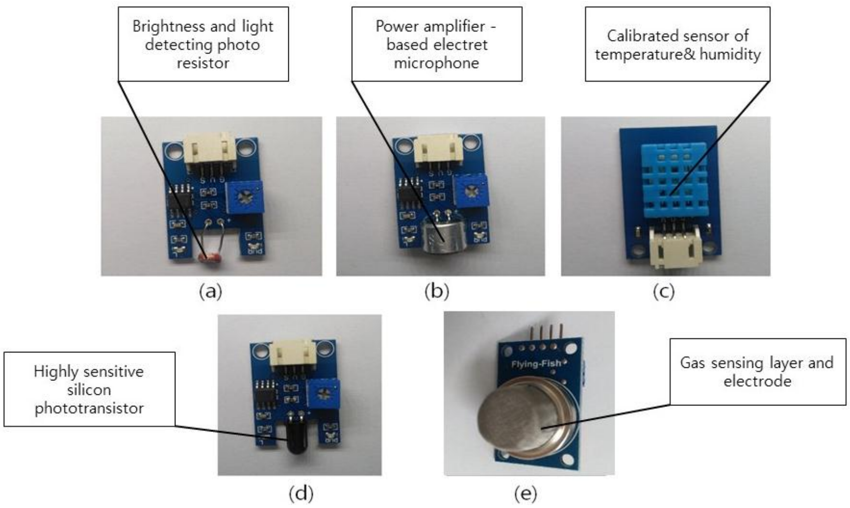
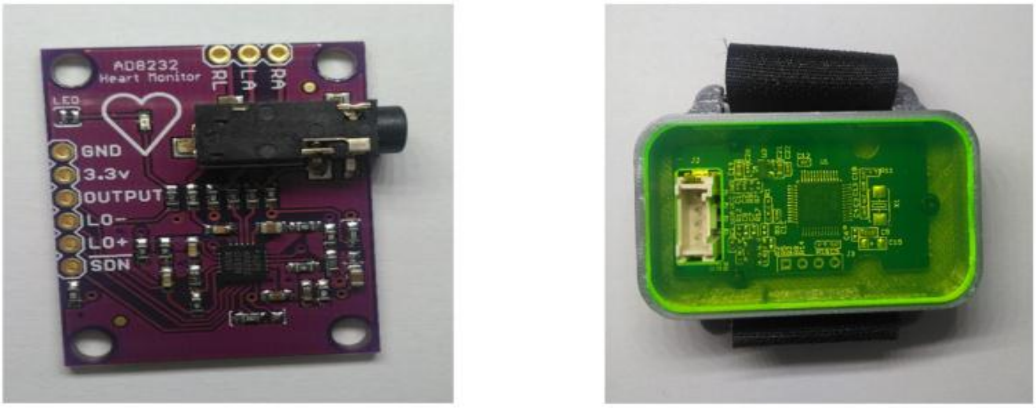


Figure 1. Environmental sensors and their parts: (**a**) light sensor; (**b**) sound sensor; (**c**) humidity sensor; (**d**) flame sensor; (**e**) fume sensor.

3.2. Biosensors

The scope of biosensors has expanded with the increasing demand for health monitoring. These sensors allow people to be aware of their health status at all times, and are used by healthcare professionals in the early diagnosis and prevention of disease [39,40]. Examples include body temperature sensors, heart-rate-monitoring sensors, electrocardiogram (ECG), electroencephalography (EEG), electromyography (EMG) sensors, blood pressure sensors, and glucose level sensors.

A heart-rate-monitoring module (Figure 2a) can be used to measure the electrical activity of the heart, and is intended for use in extracting, amplifying, and filtering bio-potential signals to generate the heart rate [41]. Typically, heart monitors require the use of biomedical sensor pads and cables. The finger-clip heart rate sensor shown in Figure 2b is a high-performance optical biosensor that measures the change in the movement of blood in the body. Biosensors are common in medical electronics intended for indoor use to monitor the patient's health [42].



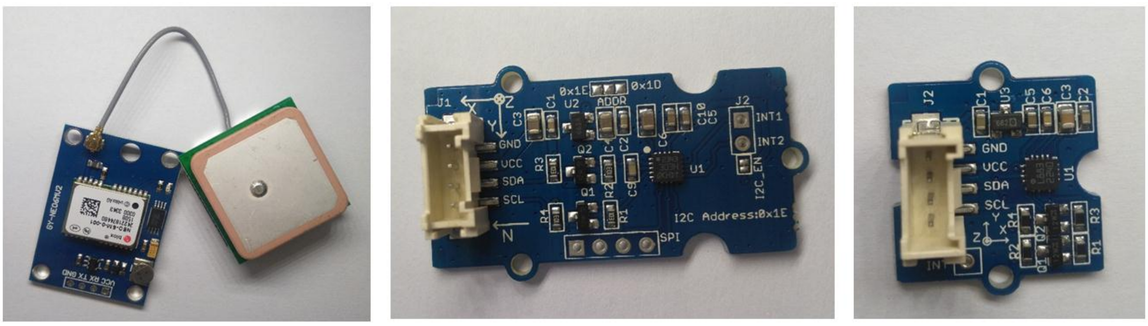
(**a**) (**b**)

Figure 2. Optical biosensors: (**a**) electrocardiogram (ECG) heart-monitoring sensor; (**b**) finger-clip heart rate sensor.

3.3. Position- and Location-Tracking Sensors

Location- and position-tracking sensors [43] (i.e., GPS, altimeter, magnetometer, compasses, and accelerometers) are the most common type of sensors on wearable devices, such as activity trackers, smartwatches, and even medical wearables where they are used to check the physical activity and health of patients. A GPS module (see Figure 3a) is a three-axis sensor used in spatial navigation that can determine location, altitude, and speed at any time and in most weather conditions. However, in the mining industry, there are few examples of the use of GPS (only in outdoor open-pit mines) modules for tracking purposes [44–47]. Because signals needed for GPS modules are not available indoors, they are considered unsuitable for underground tracking systems. A compass (see Figure 3b) is a simple magnetometer that defines the direction of the climatic magnetic field.

A magnetometer sensor can be used to measure the magnetic field at a specific location. As it can detect ferrous metals, it can be used for tracking metallic vehicles [48] and human body motions (when jointly used with accelerometer and/or smartphones) [49–51]. Another common type of inertial sensor is an accelerometer, which has an extended range of sensing capability. They are available in one-, two-, three-, or six-axis implementations (see Figure 3c), and have high capability in fall detection and safety management applications.



(a) (b) (c)

Figure 3. Location-tracking sensors: (**a**) global positioning system (GPS) module; (**b**) 6-axis accelerometer and compass; (**c**) digital compass.

3.4. Other Sensors

Other sensors include a variety of detectors and sensors available on the market, usually found on consumer wearable devices. Wearable cameras and smart glasses are often described together with camera sensors as the main part of these devices. Communication sensor modules (i.e., Bluetooth, Radio-Frequency Identification (RFID), Wi-Fi, etc.) provide communication and data exchange features to wearable devices. These sensors are being adopted in the mining industry for tracking and other purposes [52]. Motion sensors, speed sensors, inertial measurement unit (IMU) sensors (compound unit of accelerometer, gyroscope, and, sometimes, magnetometers), ultrasonic sensors, and infrared receiver (IR) sensors (small microchips with photocells to catch infrared light) are also used as electronic components of wearable devices.

4. Applications of Wearable Devices to the Mining Industry

4.1. Current Applications in the Mining Sector

Vandrico Solutions Inc. in Canada is developing a head-mounted device similar to Google Glass that is described as the first SmartGlass application intended for the mining sector [9]. The project is expected to be used in 50 mines around the world where the Metrics Manager™ by Motion Metrics International Corp. is currently being used. This collaboration enables the project to offer special features, and improve the efficiency and safety of operations in hard rock mining. Examples of the applications supported by the smart eyewear include time management for controlling mining equipment, free access to the most commonly accessed information, and production process control and monitoring, such as conveyor belt loading supervision. The core of the application is based on the identification of location by GPS and information exchange through the communication features of the glass. Although the hardware of the project has not yet been decided, the company focuses on the smart HUD system of glasses by Recon Instruments. The smart display is intended to allow each user to interact with the environment hands-free and notify about the mining operation most needed. The camera on the device can be used to take images or videos in emergency situations, such as mine machine maintenance or repair, and send them to administration staff for supervision or advice.

Deloitte Wearables is another Canadian company with a mining-site-focused wearable project [11]. It is different from other similar companies as they are targeting safety goals with another type of wearable smart helmet. This new wearable device is lightweight, and can be attached to the back or front of a miner's helmet. It contains sensors to detect levels of hazardous gases in the air, a radiation sensor, a temperature and humidity sensor, and other sensors depending on the type of mine. In addition to providing an alert system with yellow to red lights for emergency situations, the helmet facilitates communication between managers and miners. The accompanying software platform will allow managers to track the device and monitor the actions of workers. This project is being developed in partnership with two other companies, Cortex Design and Vandrico. In turn, the Vandrico team built the software platform with a tracking system for the workforce and Cortex Design produced the project's hardware system [11]. The Cortex team visited a mine in Sudbury and held close conversations with the miners to ask for suggestions for designing the device to meet challenges at the mining site. The tracking system is based on radio frequency identification tags for the administration to obtain information about the locations of workers for better management. The device is fully rechargeable, and can be controlled even with gloves on. The smart gadget senses body gestures to accomplish tasks.

In South Africa, the mining safety systems company Expert Mining Solutions is developing the "Life" wearable, which incorporates sensors and actuators to acquire the brain activities of equipment drivers (haul trucks, excavators, dozers, graders, and water trucks) and monitor fatigue at coal mines operated by Anglo American Metallurgical Coal [12]. The Life can accurately measure brainwaves of the wearer and store data for medical analysis. The device targets mine operators to focus on possible risks in the mining environment. It detects the lack of signals in the brain, such as to determine sleepiness (the system uses an advanced measurement tool for the operator's resistance to sleep), diet, or medical conditions that may cause fatigue in workers. When this device is deployed, it is expected that the rate of accidents will be reduced and the awareness of vehicle drivers will increase. The technology in Life was developed at four universities, and has now been certified to detect fatigue with an almost 95% accuracy. The device has been used in trials over the past five years in mines operated by Assmang in the Northern Cape, which was the first official use of wearables in the South African mining industry.

Respirable silica dust, also known as respirable crystalline silica (RCS), is a natural substance found in rocks during the mining process, and is a major harmful contaminant for miners. This fine dust causes lung-related chronic diseases [53,54]. To analyze the most hazardous areas of a mine site and develop prevention tactics, a wearable dust assessment technology known as the Helmet-Cam has been tested at two industrial mineral mines [13]. The device consists of a video camera attached to the helmet, a real-time, data-logging, respirable dust monitor on the worker's belt or backpack, a video monitor, and a safety vest to hold the entire system. When the captured video and dust data are uploaded to software, it automatically analyzes the concentration of respirable silica dust in the air.

4.2. Application to Mine Safety Management

The approaches described thus far are one-sided or do not address complex needs in areas of safety, communication, and occupational health in the mining industry. Therefore, from the perspective of providing wearable devices for mine workers to improve safety, this study proposes a wearable safety management system for miners (Figure 4). The system includes the combined utilization of several wearables (Figure 5) and is intended to improve safety, provide hands-free operation, and help monitor occupational health. The system consists of the following: a sensor-equipped safety vest (Figure 5a), smart eyewear (Figure 5b,c), a smart helmet (Figure 5d), and a commercially available Android system smartwatch (Figure 5e). The proposed system can be expanded by additional sensors or electronic equipment, or reduced in complexity according to the specific needs of the worker and mine operations.

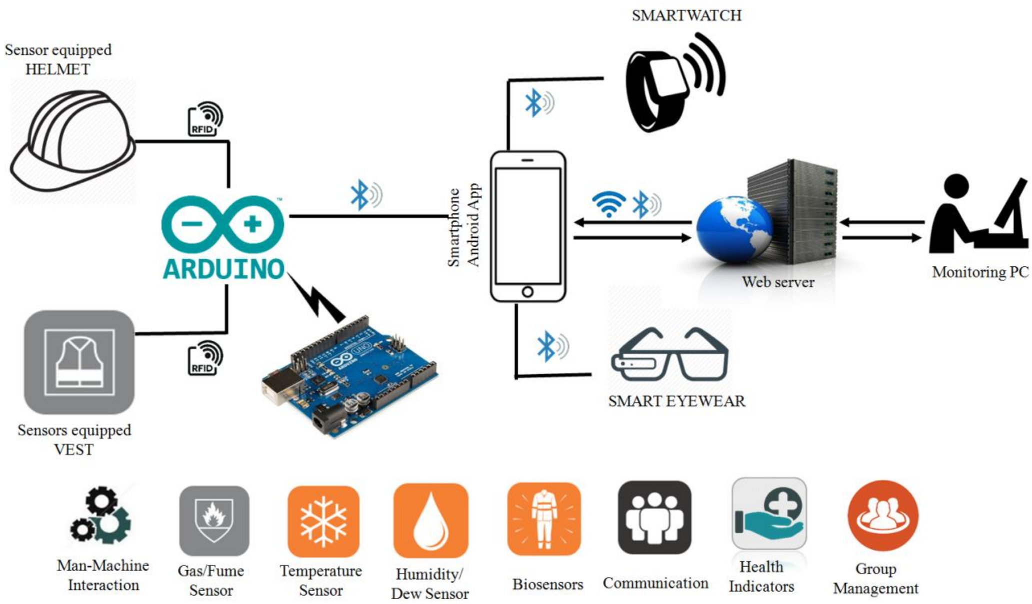


Figure 4. Wearable technology-integrated embedded wearable safety communication system.

Figure 5. Proposed embedded wearable system shown at a mining site: (**a**) sensor-equipped mine safety vest; (**b**) miner wearing Recon Jet Smart Eyewear; (**c**) miner using Epson Moverio BT-2200; (**d**) sensor-equipped safety helmet; (**e**) smartwatch.

The safety helmet is worn by all mine workers during work shifts regardless of the type of mine, underground or open pit. Therefore, almost all main sections of the system (data transmission and controller board parts) are designed on the helmet, and other wearables are connected to the board through wireless connection modules using either Bluetooth or RFID. As Arduino is a widely used hardware and easy-to-use open-source software platform in most electronics projects, the Arduino Uno board was used as an example to control the microcontroller board in the proposed system. To allow the worker to operate without worrying about turning the light emitting diode (LED) head lamp on and off on the helmet or changing brightness according to the luminosity of the environment, a lighting section not displayed on the safety helmet (see Figure 4) can be included as part of the system using a pair of light sensors.

If there is need for brain activity sensors, the inside flat border of the helmet is the most appropriate location for sensor installation as it is in permanent contact with the head of the wearer. The equipment for the detection of temperature, humidity, sound, air quality, and fumes should be mounted on the helmet in a special waterproof enclosure. Because the miner needs to be aware of the sensor results at any given time, the information should be displayed as numbers or words on a screen, or liquid crystal display (LCD), attached to the safety vest. The alert system, which can be also supported, sounds a loud alarm (the structure of the emergency notifications is explained in detail below) in emergency situations to notify miners of danger.

Although there is no commercial wearable clothing for the mining industry in particular, the regular safety vests of miners can form a kind of smart clothing when smart electronic components are used. The attached environmental sensors (sound sensor to measure the noise level of the environment and dust sensor to check the concentration of hazardous particles in the air) and biosensors (body temperature sensor and pulse rate sensor to monitor the miner's basic physiological conditions) enable the real-time measurement of both environmental conditions and the health of the wearer.

The most important part of the system is the smart glasses that, as they do not require operation with the hands, enhance efficiency and boost the decision-making abilities of the workforce. In this system, eyeglasses are intended for use in mining sites with four goals:

- a screen displaying important notifications (the notifications are sent to the glass by mobile phone over Bluetooth);

- the scanning of the situation through the glasses and providing specific guidelines to follow (for example, in site supervision and monitoring conveyor belt operations);
- using the eyewear as a first-person camera to capture videos and photos for job-related purposes (in cases when there are no smart glasses, a small wearable camera suited for mounting on the helmet can be used for the same purpose);
- using the screen as a navigation display for location (not suitable for underground mines).

To achieve the above targets via smart glasses, a special software package should be developed with these features to freely and securely exchange data with applications on the mobile phone.

The mobile software package is a portal that bridges all components of the system and stores data acquired from them for further processing and analysis. For the mobile software package of the proposed system, the Android Operating System (Android OS) by Google Inc. was selected, as the company also has an operating system for smartwatches called Android Wear. The smartwatch performs similar functions to the smartphone in terms of notifications and monitoring. However, as the watch also has an internal heart rate sensor, this is proposed as another health indicator featured by the system.

The application displays values for the entire system and provides notifications of risk events for the staff to monitor and manage. To evaluate the degree of engineering risk in a hazardous mining environment and facilitate greater interaction and awareness among the mine workers, alert notifications are divided into three modules: (1) notification of personal risk; (2) notification of risks in the area; and (3) notification of risks in other areas (neighborhoods) (see Figure 6).

The tasks include tracking the device to ensure the staff are not in risky situations (real-time proximity detection), checking the mining conditions (temperature, humidity, hazardous gas, and fume levels in the air), providing information on health indicators (heart pulse, body temperature, blood pressure), and, in case of emergency, providing an evacuation alert or initiating other accident prevention techniques. The system is expected to support various wireless technologies, such as RFID, Bluetooth, and Wi-Fi to transmit the collected data from the sensors to the management-monitoring system.

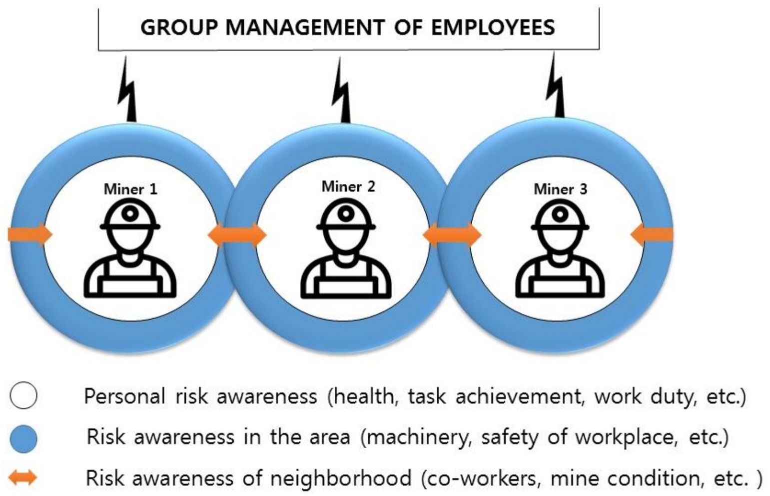


Figure 6. Group management and improved risk awareness among miners.

4.3. Other Possible Applications

Other possible applications of wearable devices with sensors in mining are suggested in Table 2. In the multitasking environment of mining sites, operators and supervisors can benefit from the use of smartwatches as notification alert tools or communication gadgets to accomplish their work duties more effectively or report on important issues directly from their watches. With a specially developed software package for mining sites, smartwatches can also be used as terminals to show navigation information for logistics. In mines, if mining equipment needs to be repaired, which usually requires a long time and partly stops the mining operation, this can be carried by the site workforce using smart glasses. The mine worker has only to follow the instructions on the display. The eyewear gadgets can be used to continuously monitor conveyor belt operations, control task achievement, and even for site supervision.

Table 2. Possible applications of wearable devices and sensors in the mining industry.

Wearable Device						Sensor	Application
S.W. [1]	S.E. [2]	W.C. [3]	S.C. [4]	F.T. [5]	M.W.D. [6]		
Δ	Δ	Δ				IMU [7] sensor, control sensor, IR [8] sensor	mining equipment management
Δ	Δ	Δ				camera sensor, navigation module, accelerometer, speed sensor, magnetometer, position sensor	transport and logistics management
Δ	Δ	Δ				proximity/motion sensor, ultrasonic sensor, IR sensor, camera sensor	process monitoring & reporting
Δ	Δ	Δ				camera sensor, control sensor, navigation module, IMU sensor	site supervision
Δ	Δ	Δ					supply chain management
Δ	Δ	Δ					task achievement monitoring
	Δ	Δ					conveyor belt monitoring
	Δ	Δ	Δ			camera sensor, IMU sensor, navigation module	labor education and training
	Δ	Δ	Δ				emergency preparedness
Δ	Δ	Δ				communication module, camera sensor	communication & data management
	Δ	Δ	Δ			camera sensor, motion/proximity sensor, temperature sensor, humidity sensor, gas sensor, air pressure sensor, radiation sensor	risk and change management
	Δ	Δ	Δ				operational safety monitoring
	Δ	Δ	Δ		Δ		mine rescue training/operations
			Δ	Δ	Δ	pulse rate sensor, ECG [9] sensor, EEG [10] sensor, body temperature sensor, sound sensor, blood pressure sensor, glucose level sensor, exhalation sensor	occupational health monitoring
			Δ	Δ	Δ		occupational disease prevention
		Δ	Δ			camera sensor, dust sensor, humidity sensor	dust monitoring
		Δ	Δ			camera sensor, sound sensor	noise monitoring
		Δ	Δ			temperature sensor, gas/fume sensor, humidity sensor, exhalation sensor	air flow monitoring (ventilation)
	Δ	Δ	Δ			light sensor, camera sensor, control sensor	facility management (lights, pump etc.)
		Δ	Δ				mine equipment service and maintenance

[1] S.W.—smartwatch; [2] S.E.—smart eyewear; [3] W.C.—wearable cameras; [4] S.C.—smart clothing; [5] F.T.—fitness trackers; [6] M.W.D.—medical wearable devices; [7] IMU sensor—inertial measurement unit sensor; [8] IR—infrared receiver sensor; [9] ECG—electrocardiogram; [10] EEG—electroencephalogram.

In mining sites, wearable cameras can be applied for many purposes according to the characteristics of the mine operation. In underground mines, they can be used for dust monitoring, supply chain management, and safety monitoring. In outdoor environments, the cameras in most cases are useful tools for site supervision and process control. Nearly no smart clothing products are available on the market for the mining sector to wear in a workplace. However, attaching some biosensors to miners' safety vests for health checks, radiation and gas sensors on the safety helmet, and a belt with unique proximity detection features can lead to a healthier workforce, provide a safer work environment, and, consequently, enhance the job satisfaction of the miners.

As most activity trackers have step counting and accelerometers, they can be useful in fall detection systems for emergency situations encountered by mine workers. Furthermore, the biosensors in the fitness trackers are well-suited to measure the daily health status of the staff, which prevents occupational disorders. At present, most wearable medical devices are used to log people's activities and exercise regimens, and measure core biomedical data. However, some support an expanded range of possible measurements. For example, the remote monitoring of mine workers using wearable medical devices helps the early diagnosis of illnesses and timely treatment.

5. Conclusions

In this study, a review of wearable device technology and its potential deployment in the mining industry was conducted. It also suggested a wearable safety management system for miners and other possible applications to the mining industry. A few initiatives are underway to introduce wearable technology to mining. The successful utilization of these advanced devices in other sectors suggests that they can be used to provide practical solutions.

In mines around the globe, a lack of communication and safety issues frequently cause miners to experience life-long injuries and even death [55]. It was difficult to analyze actual mining environments due to the use of vague techniques and unpredictable mining conditions therein. However, the deployment of advanced technologies in the form of wearable devices can help regularly monitor the mining process, create a healthier and safer workplace, and improve the professionalism of personnel. If wearable technologies are successful in addressing the challenges of safety, occupational health, and communication at mining sites, there is potential for the conventional concept of a "hazardous mine" to evolve into a modern and safe "innovative workplace" featuring high efficiency and increased production. Therefore, wearable devices should be further used in the mining industry.

Some conditions need to be considered when proposing wearable device technology for mining. In the first, as electronic devices usually contain a variety of metals and chemical compounds, such as beryllium, cadmium, metal chromium, and lead, there is a risk of exposure and serious harm to users' health [56]. The second features specific government regulations and rules in each country for the use of electronic devices in mining. Because of environments containing flammable materials, strict regulations are in place for the use of electronics in underground coal mines in most countries. According to the Occupational Health and Safety Act of Underground Mining Regulations in Canada, portable, flameproof electrical equipment can be installed if certified by an engineer 12 months before its first use at a mining site in zones with no risk of explosion (the equipment should be designed not to come into contact with coal dust below 150 °C), and can only be used by trained personnel [57]. In the US, the use of some electronic devices in mining sites is carried out after specific testing according to rules laid out by the Mine Safety and Health Administration (MSHA) of the Department of Labor [58]. Similar restrictions apply to the use of signal apparatuses in underground mines in the Mines, Quarries, Works and Machinery Regulations of Botswana [59]. Although some restrictions are in place on the use of electronic devices in underground mines, the global mining community still thinks that the industry can benefit from technological advances in terms of efficiency and management [60–64].

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