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Review

Review on Improvements to the Safety Level of Coal Mines by Applying Intelligent Coal Mining

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Abstract: China suffers the worst coal mine disasters in the world. Lots of miners lose their lives or suffer occupational injury. Fortunately, China is developing vigorously intelligent coal mining, which is the combination of traditional coal mining and the latest technology. Mining expects to relieve or solve coal mine safety, health and intensive labor issues and ensure energy security by applying intelligent coal mining. This paper fully reviews the promotion of intelligent coal mining to coal mine safety. Firstly, a brief history of intelligent coal mining is introduced. Then the safety motivation of the intelligent coal mine is discussed in four perspectives, including current the coal mine safety tendency, the positive impact of mechanized coal mining on safety, coal mine safety conception of "Mechanization Replacement and Automation Reduction", and government initiatives. The intelligent prevention and control scheme of major disasters matching intelligent coal mining are also reviewed in the present paper, including intelligent gas extraction, intelligent coal and gas outburst/rock-burst prevention, and the real-time monitoring of water diversion fissure zone. Finally, the positive impacts of intelligent coal mining on safety are evaluated. Compared with traditional longwall face, the number of miners of coal cutting shift is reduced from 20~30 to 5~7, and the working environment is greatly improved. The statistics have shown that the employees in large coal mines, the mortality rates per 10^6 tons of coal output, and the number of deaths decreased by 33%, 72.2%, and 66.9% during the period of rapid development of intelligent mining technology (2016–2021). In the future, more and more key technologies and management skills should be introduced, aiming at workless mining and the intrinsic safety of the coal mine. This paper provides a way for safety researchers around the world to understand the tendency of coal mine safety in China.

Keywords: intelligent coal mining; safety level; safety conception; national policy; mining disaster

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Citation: Wu, X.; Li, H.; Wang, B.; Zhu, M. Review on Improvements to the Safety Level of Coal Mines by Applying Intelligent Coal Mining. *Sustainability* **2022**, *14*, 16400. https://doi.org/10.3390/su142416400

Academic Editors: Hui Liu, Longxing Yu, Fuqiang Yang and Chao Chen

Received: 14 October 2022
Accepted: 2 December 2022
Published: 7 December 2022

1. Introduction

China is relatively rich in coal and poor in oil, and it is low in natural gas and suffers from uranium deficiency [1]. This energy condition and the technical and economic feasibility of coal mining have determined the status of coal resources as the main energy in China in the long term [2]. Meanwhile, serious coal mine safety concerns have arisen. Previous studies have revealed that the factors of miners' unsafe behavior account for more than 95% in coal mine accidents [3–5]. Various advanced safety management methods have been implemented in coal mines for many years that greatly improved our coal mine safety level. However, coal mine safety accidents are still high compared with other major coal producers due to the fact that 90% of coal is mined underground. Underground coal mining means more deadly hazards due to confined space, toxic and harmful gases, mine water, machinery, surrounding rock, and other dangerous sources [6,7].

In addition, the mining depth is extended at an average rate of 10–25 m per year [8,9]. Deep underground, the working conditions deteriorate sharply, including high geo-stress, geo-temperature, karst water pressure, and gas content. This means that coal mines will be exposed to greater safety risks and miners' productivity and safety vigilance will fall, thus posing a great challenge to national energy security and coal mine safety [10]. Currently, the main coal-producing countries in the world are using a new generation of intelligent technology to improve the safety level of coal mines [11–15]. China has an urgent need to strengthen the management and technology to guarantee secure, efficient, eco-friendly coal mining. The intelligent coal mining has gained popularity in industry and academia in recent years. Coal mine operators and government authorities hope to reduce the number of coal miners and improve the safety level of coal mines by implementing intelligent coal mining technology.

Several system frameworks of intelligent coal mining have been proposed by renowned mining experts. Lots of latest technologies, such as Internet+ [16,17], 5G [18,19], Artificial Intelligence, Internet of Things, and Cloud Services, have been applied to coal mining. Huang (2016) proposed an unmanned mining production mode with "unmanned operation and manned patrol" through visualized remote control [20]. Fan (2017) discussed the key technologies of intelligent integrated mechanized coal mining, including automation moving and remote manual control of hydraulic support, shearer memory cutting and remote manual control, longwall face video monitoring, automatic centralized control of longwall face, intelligent integrated liquid supply control, and automatic pre-supporting [21]. Wang et al. (2019) summarized four kinds of intelligent coal mining modes which are suitable to different geology and coal seam conditions. There is the intelligent unmanned mining mode suitable for thin and medium coal seams, the intelligent and efficient man–machine cooperative patrol mode suitable for longwall face with a large mining height, and the intelligent operation and manual intervention coal caving mode suitable for fully mechanized caving longwall face and mechanization and intelligent combined mining mode for coal seam with complex conditions [22,23]. Ge et al. (2021) proposed a navigation cutting theory and technical framework suitable for automatic driving of deep coal seam shearers [17,24].

This paper aims to comprehensively review the positive impact of intelligent coal mining on coal mine safety in China. First, we introduce the development of intelligent coal mining briefly. Then we analyze the safety motivation of intelligent coal mining. After that, some advanced intelligent prevention and control schemes of major disasters matching intelligent coal mining are reviewed. Finally, we evaluate the positive impact of intelligent coal mining on safety. This paper provides a way for safety researchers around the world to understand the tendency of coal mine safety in China. Meanwhile, the development experience of intelligent coal mining can also provide reference for other developing countries in mining safety.

2. Development of Intelligent Coal Mining in China

Intelligent coal mining, which has intelligent-sensing, learning, decision-making, and controlling features, is one of the core goals of the intelligent mine. In other major coal mining countries, such as Australia and the USA, researchers and engineers tend to use the term "automatic" to describe advanced coal mining methods which are based on information and digital technologies [25,26]. The reason for popularity of the term "intelligent coal mining" is that China puts more emphasis on advanced coal mining technology to guarantee national energy security and improve coal mine safety at the same time. The research and practice of intelligent coal mining in China started around 2010. Since then, a series of key technologies have been developed, and several representative engineering practices have been implemented. In this section, we introduce the development history of intelligent coal mining in China briefly, including the following: (1) initial stage—memory cutting and remote video monitoring [27]; (2) current status—geological navigation [28]; and (3) future tasks—workerless mining [29,30]. The basis of the stage division of intelligent coal mining mainly includes the following two aspects: ① the landmark industrial test in the development of intelligent coal mining and ② the consensus of the majority of intelligent mining experts at present.

2.1. Initial Stage: Memory Cutting and Remote Video Monitoring/Controlling

During the twelfth Five-Year Plan (12th FYP) period (2011–2015), the China Coal Technology & Engineering Group Corp (CCTEG) and several coal enterprises had collaborated to develop the first-generation intelligent coal mining technology, i.e., memory cutting and remote video monitoring and controlling. The mining conditions detected by various sensors and commands issued by miners are transmitted between the longwall face and control center through the Industrial Ethernet Ring Net. The technological framework of this technique is shown in Figure 1 [20]. The system consists of three parts: coal mine commanding center, roadway monitoring and controlling center, and integrated mining machinery. The coal mine commanding center acts as an integrated visualization and controlling platform, whose functions include inputting monitoring data, displaying machinery and mining dynamic, and sending overall controlling commands. The roadway monitoring and controlling center is in the intake airway. The function of this center is to monitor and control mining machinery, which includes the automation of shearer, powered roof supports, face conveyor, etc. The integrated mining machinery coordinates with each other to realize the whole process of coal mining, including coal cutting and transportation, dust capturing, roof supporting, and other operations.

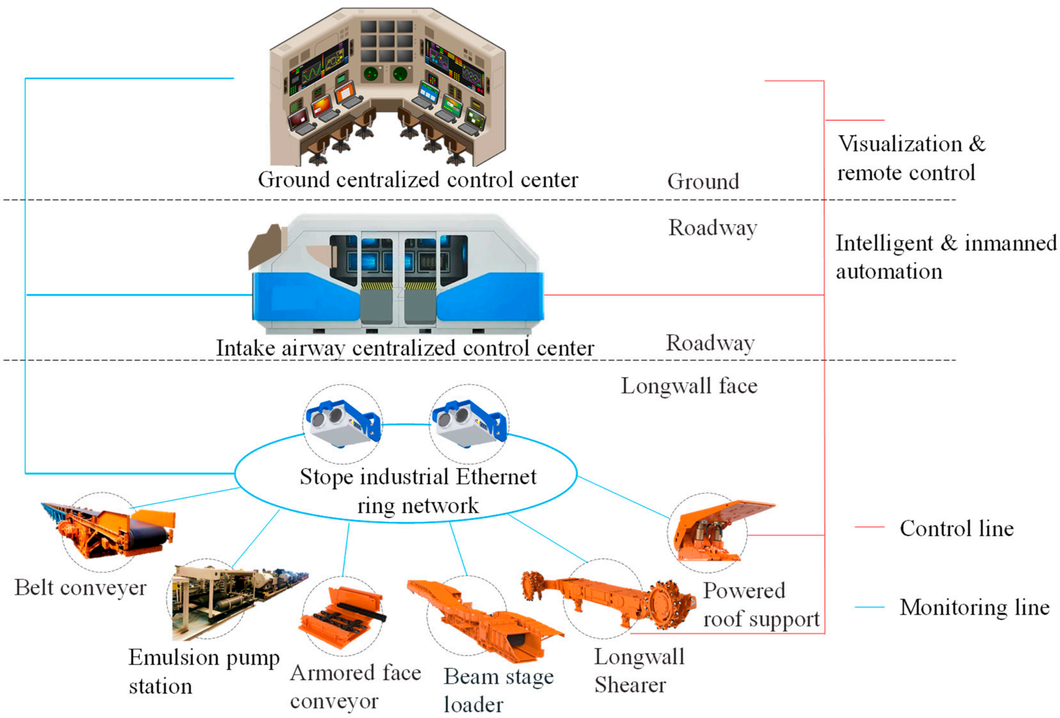


Figure 1. Technical framework of visual remote intervention mining [20].

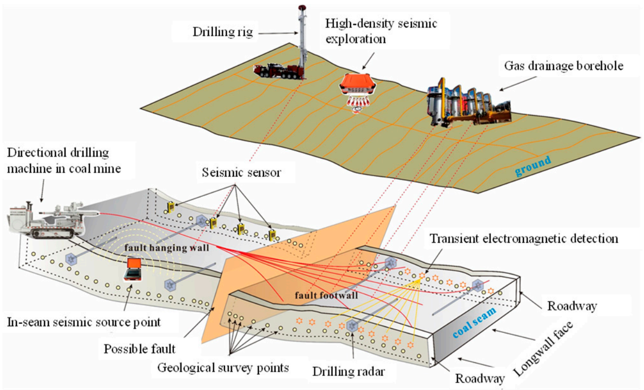
The intelligent coal mining featured with memory cutting and remote video monitoring/controlling has been widely used in several mine enterprises, including Huangling, Shendong, Yangquan mines, etc., since 12th FYP. From the view of coal mine safety, the following two key advancements have been made through the research and practice of intelligent coal mining [20,31]:

(1) This advanced mining method moves miners from the dangerous longwall face to the safe and healthy control center located in the intake airway.
(2) The number of miners of a coal cutting shift is dramatically reduced from 30~50 to 5~7, which provides a strong guarantee for the safe mining.

However, it is important to point out that the above automatic mining method is only suitable for the longwall panel with stable coal seam thickness, small inclination, and fault-free and caved pillar-free.

2.2. Current Status: Transparent Geological Navigation

Considering the inadequate adaptability of the abovementioned first-generation intelligent coal mining, the coal operators and academia are actively trying to upgrade memory cutting to planned cutting based on transparent geological navigation in the 13th and 14th FYP periods. The technological framework of this technique is shown in Figure 2 [28], and the general idea of transparent geological navigation consists of three parts:



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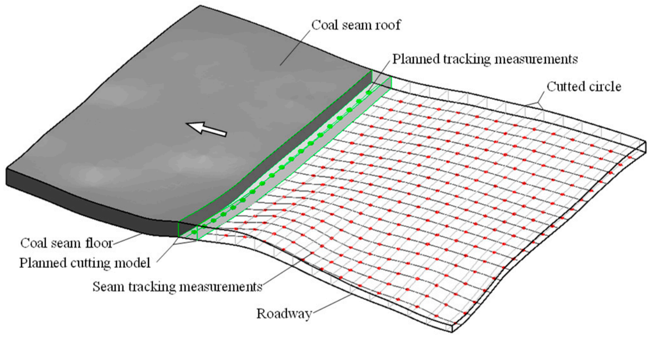

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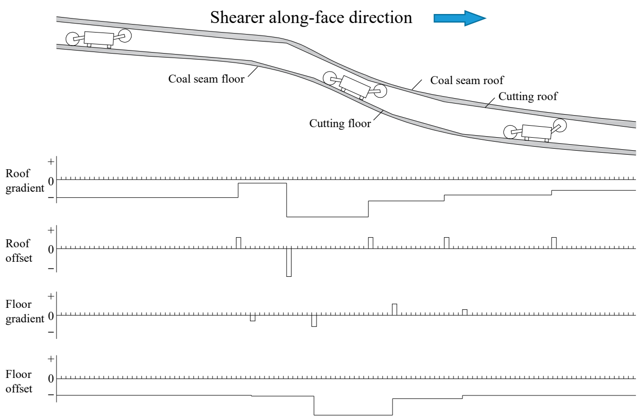

(**c**)

Figure 2. Intelligent coal mining based on transparent geological navigation. (**a**) Geological survey of longwall panel. (**b**) High-precision coal seam model. (**c**) Digital coal cutting.

(1) The first step is to construct a high-precision coal seam model based on multi-source geological data, such as roadway revelation, bore logs, and seismic survey data [32,33].

This model locates the un-mined seam boundaries in the 3D space (Figure 2a). In addition, the abnormal geological conditions can be predicted based on the abovementioned data.

(2) The second step is to establish a big data analysis/decision platform to guide coal mining. The tasks of the platform include the following three (Figure 2b): (i) amending coal seam model-based extraction profiles, coal interface, and seam tracking measurements obtained during the mining process; (ii) generating the cutting model based on the seam model and mining scheduling; and (iii) implementing accurate machinery control, fault self-diagnosis, and production decision-making based on historical production data and artificial intelligence.

(3) The third step is to collect the state parameters of coal mining machinery based on the various embodied high-precision sensors, such as the inertial navigation system, 3D laser scanner, radar, etc. The control commands and machinery working conditions are transmitted between the longwall face and control center via industrial Ethernet (Figure 2c) [34]. Then the automatic coal mining machinery works coordinately.

Currently, lots of coal enterprises are working together with research institutes to optimize this technology. They hope to improve the adaptability and reliability of intelligent coal mining.

2.3. Future Tasks: Workerless Mining

The goal of coal mining is workerless mining. Several Chinese coal mining experts have proposed different top-level technical frameworks. Yuan (2017) proposed a new future mining mode, precise coal mining [30]; that is, a variety of coal mining factors, such as disaster warning and controlling, environmental protection, intelligent automation, geology, transportation, etc., are operated precisely through on intelligence, intelligent control, the Internet of Things, cloud computing, and big data. Wang et al. (2019) put forward a more specific top-level technical framework consisting of an underground positioning and navigating system, underground video and 3D virtual reality remote control platform, operation system of integrated mechanized mining machine, and mining robot group coordinated command platform [29].

3. The Safety Motivation of Intelligent Coal Mining

3.1. Coal Mine Accident Characteristics and Safety Tendency

3.1.1. The Characteristics of Coal Mine Accidents

In this section, the coal mine accident characteristics are analyzed based on 483 deadly accidents during 2015–2019, as reported by the media [35].

For most of the coal mines, the working hours of morning, middle, and evening shifts are 8:00–16:00, 16:00–24:00, and 0:00–8:00. Middle and evening shifts are the production stage in which the main work is coal mining and roadway excavation. The general work of the morning shift includes machinery maintenance and quality standardization. Figure 3 shows the statistics of accidents and fatalities on different periods of time. Most of the deadly accidents and deaths happened during the rest periods, for example, from 00:00 to 4:00, from 12:00 to 14:00, and from 20:00 to 24:00. If the working shifts are changed to be more suitable for physiological rest rules, it is reasonable to believe that the deadly accidents would fall.

Table 1 shows the fatalities, number of accidents, and average fatalities of different types of accidents. Gas explosion and fire, coal and gas outburst/rock-burst, roof fall, and water inrush have caused the most fatalities. Moreover, gas explosion/fire, rock burst, coal and gas outburst, water inrush, and poisoning and suffocation are most likely to induce major and the abovementioned accidents. It should be noted that these accidents tend to happen during coal cutting and roadway excavation periods. These types of accidents tend to lead to mass casualties and property losses. If a reasonable number of coal miners are replaced by automatic machinery, it is reasonable to believe that major accidents would fall. Therefore, it is urgent to improve the automation and intelligentization of coal mines to improve production efficiency and promote coal mine safety.

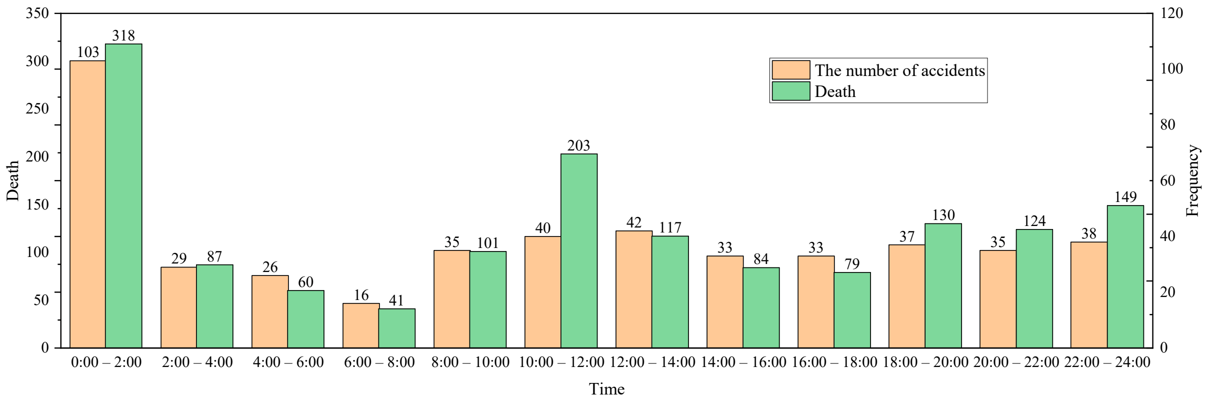

Figure 3. The accidents and fatalities on different periods of time based on 483 deadly accidents during 2015–2019, as reported by media.

Table 1. Fatalities, number of accidents, and average fatalities of different types of accidents based on 483 deadly accidents during 2015–2019, as reported by media.

Type of Accidents	Fatalities	Number of Accidents	Average Fatalities per Accident
Gas explosion, fire	458	64	7.15
Coal and gas outburst, rock-burst	204	34	6.00
Roof fall	181	94	1.93
Water inrush	171	36	4.75
Poisoning and suffocation	139	35	3.97
Transport accident	105	69	1.52
Electromechanical accidents	80	54	1.48
Blasting accident	17	6	2.83
Wall caving	7	5	1.40
Others	130	69	1.88

3.1.2. Safety Challenges Posed by Deep Coal Mining

As China's economy grows rapidly, the demand for coal increases continuously. The average depth of a coal mine extends at an average speed of 8–12 m/a, and the extension speed in the developed east provinces reaches 10–25 m/a. Currently, there are 50 coal mines whose mining depth goes beyond 1000 m, according to statistics.

Compared with shallow mining, deep mining has more serious risks, including harsh working conditions, serious safety situations, and expensive production costs. Deep in the underground, rock and coal seams are in the geological environment with high geo-stress, geo-temperature, karst water pressure, and gas content. Moreover, coal mining will trigger much more frequent dynamic disasters, such as coal and gas outburst, rock burst, mine water inrush, and roadway deformation. Multiple hazard coupling is another trend of deep coal mining that is a disaster which tends to induce a variety of secondary disasters. What is more, spontaneous combustion and geothermal disasters are becoming more and more serious. All of the abovementioned detrimental factors not only weaken miners' productivity, but also pose a serious safety challenge to coal mining.

To break the vicious circle of deteriorated working conditions, lower productivity, and the need for more miners and increased unsafety, coal mining experts hope to develop intelligent coal mining to tackle or alleviate risks posed by deep mining.

3.2. The Safety Conception of Intelligent Coal Mining: "Mechanization Replacement and Automation Reduction"

China's coal mining industry has been transforming to a technology-driven model from labor-intensive model. Coal mining productivity is low, and safety is poor compared with advanced coal mining countries such as Australia, Germany, and the United States. As early as in 2006, the average mining productivity in America had been more than 6 tons per coal miner per hour, or more than 48 tons in an 8-h day [36]. However, the productivity at the end of 12th FYP (2015) was 840 tons per coal miner per year, or less than 1 ton per coal miner per hour.

In June 2015, the former State Administration of Work Safety (SAWS) (current Ministry of Emergency Management, MEM) launched a three-year special action named "Mechanization Replacement and Automation Reduction" [37]. The goal is to replace manual operation with mechanized production and reduce front-line workers with automatic control in high-risk industries, including coal mines, chemical factory, metal non-metallic mines, and fireworks. For coal mining, there are four aspects, mechanized and automated (M&A) excavation of rock/coal roadway, M&A of coal mining, automation auxiliary transportation, and intelligent monitoring and controlling system.

So far, 901 modern coal mines (underground or open-pit coal mines), which contribute 56.42% of coal production, have been developed. The mortality rate per million tons of this part of coal production is 0.0015. State and private coal mine operators embraced the conception of "No miner, no accident" (Figure 4). Figure 4a,b shows the traditional longwall face. Figure 4c,d show the intake airway and ground centralized control centers by applying intelligent coal mining. Intelligent coal mining, which decreases miners in the longwall face by more than 50% is the key to further promoting the construction of modern coal mines.

Figure 4. The safety conception of "No miner, no accident".

3.3. Government Initiatives Boosted the Intelligent Coal Mining

3.3.1. China Coal Mine Robot Development Plan

The National Coal Mine Safety Administration issued the *China coal mine robot development plan* in Jan 2019 [38]. This guideline is a supplement to the special action of "Mechanization Replacement and Automation Reduction". *Robot* means an intelligent machine featured with self-sensing, self-decision-making, self-executing, etc. Coal mine robots are classified into five categories, roadway excavation, coal mining, transportation, safety control, and rescue. The details are shown in Figure 5.

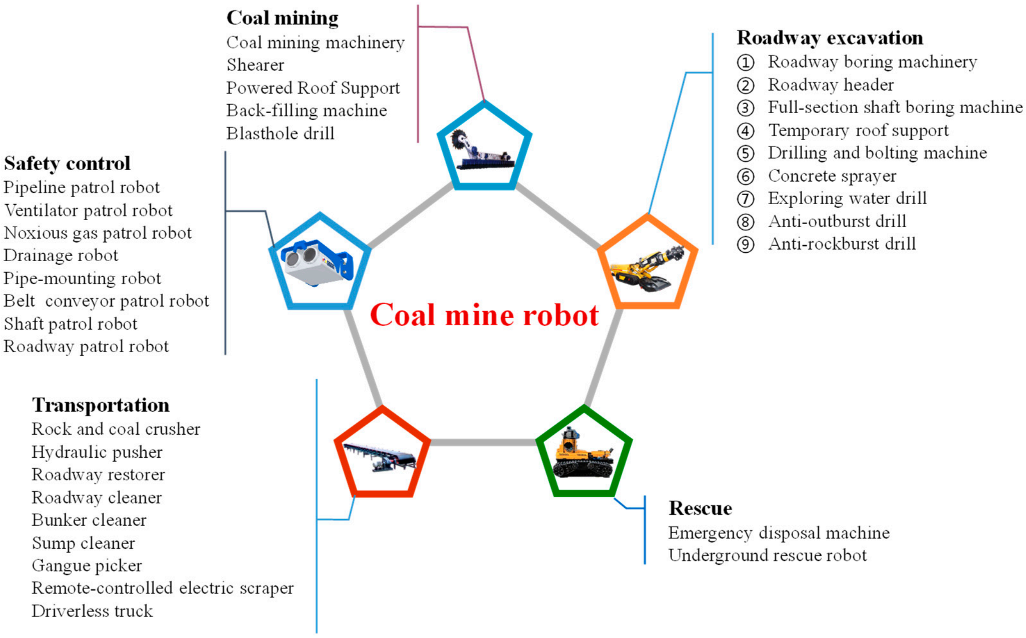

Figure 5. China coal mine robot development plan (data resources: National Coal Mine Safety Administration).

3.3.2. Energy Technology Revolution and Innovation Plan (2016–2030)

In March 2016, the National Development and Reform Commission and National Energy Administration jointly issued the "*Energy technology revolution and innovation plan (2016–2030)*" [39]. This programmatic document summarized 15 key tasks of energy policy based on national conditions, and harmless coal mining is listed first, which includes coal mine safety technology and equipment, environmentally friendly coal mining methods, and intelligent coal mining.

The document *Coal industry development plan in 13th FYP* detailed the above intelligent coal mining. The document requires mine operators to reduce major and above accidents effectively by implementing intelligent coal mining. Both the annual deaths and mortality rate per million tons should decrease 15% per year. Coal mining mechanization and roadway excavation mechanization should reach 85% and 65%, respectively, and the productivity should reach 1300 tons per coal miner per year.

3.3.3. Trend of Abolishing Night Shift and Labor Dispatching

Coal mine production is scheduled as three shifts in 24 h due to capital-intensive investment. This practice has facilitated the coal mining industry greatly. However, the living quality of tens of millions of miners has been reduced, and lots of miners lose their lives due to frequent accidents during the night shift. The following five reasons for abolishing the night shift are summarized through the questionnaire survey:

1. The night shift brings a vicious circle of reversed bio-clock and losing focus, inducing accidents.
2. Irregular sleeping pattern, overtime, and overwork induced by night shift cause serious damage to miners' health.
3. Miners want to spend time with their families and enjoy life.
4. Miners are cheated out of their chance for learning.
5. It is feasible to abolish the night shift by adopting advanced coal mining practices.

In September 2020, the National Coal Mine Safety Administration, Ministry of Human Resources and Social Security, National Energy Administration, and All-China Federation of Trade Unions jointly issued *Guidance for further normalizing coal mine labor Employment and Promoting Coal mine Safety Production* [40]. This guidance stressed that the night shift and underground labor dispatching should be abolished within three years. Obviously, this policy will exacerbate the problem of mining productivity and labor shortage further. To maintain or increase coal output, coal mine operators must improve productivity through advanced mining technology. Currently, more and more coal mine enterprises are gradually abolishing the night shift of the non-intelligent longwall face through optimizing mining design, improving labor organization, upgrading equipment and technology, and other measures.

4. Intelligent Prevention and Control Scheme of Major Disasters Matching Intelligent Coal Mining

To promote the development of intelligent coal mining, some advanced prevention and control programs of main hazards in the longwall panel scale have been put forward, especially for intelligent gas extraction, intelligent coal and gas outburst/rock-burst prevention, and the real-time monitoring of the water diversion fissure zone. These programs are important supplements to intelligent coal mining. Note that these programs are only limited to longwall panel level, rather than to a coal mine.

4.1. Intelligent Gas Extraction

Gas is one of the sources which tend to induce major disasters, including gas explosion, fire, coal and gas outburst, and poisoning and suffocation. As Table 1 showed, gas accidents cause most of the deaths. In the longwall panel scale, the pre-pumping is mainly adopted to extract and control coal seam gas [10]. The construction crafts of gas drainage drill hole are varied, mainly including parallel and scalloped drill holes along the coal seam, and down- and up-holes cross coal seam. The working air pump forms a negative pressure in the gas drainage pipes. Then gas will escape from the high-pressure coal seam to negative pressure pipes. This extraction process generally lasts 1–2 years before coal mining. This technique has been applied well and has been mandated as a mandatory operation in coal mines.

Due to the complexity of the gas drainage system, the overall operating condition of the system is susceptible to a change in the pumping load and local operating conditions. Moreover, Zhou et al. (2019) summarized the major problems of the gas drainage system [41]:

- The control of negative pressure is not optimized dynamically according to the gas pressure change, thus resulting in high negative pressure in the area with low gas concentration.
- Gas drainage management relies heavily on manual patrol, and some failures, such as borehole collapse and pipe leakage, are not easily detectable.
- An air pump cannot increase or decrease the working power adaptively according to the load, thus resulting in a lot of electricity being wasted.
- The resistance in the local pipe network is large.
- The types and volumes of gas drainage parameters being monitored are limited. What is more, manual testing dominates.

The abovementioned issues tend to reduce the gas drainage efficiency and limit the utilization of gas resources, as well as some disasters, such as pipeline gas explosion and coal and gas outburst. Therefore, Zhou (2019) proposed the concept of intelligent and accurate gas drainage, which aims at ensuring that the system operates safely, efficiently, and with low energy [41]. The gas drainage strategy, which includes the pipeline network and air pump working power, is optimized dynamically based on a pipeline network optimization algorithm; automatic valves; and the monitoring data, including negative pressure, gas flow and concentration, and valve opening data. The framework of intelligent and accurate gas drainage is shown in Figure 6. It consists of data-aware, communication, data-processing and decision-making, and control modules.

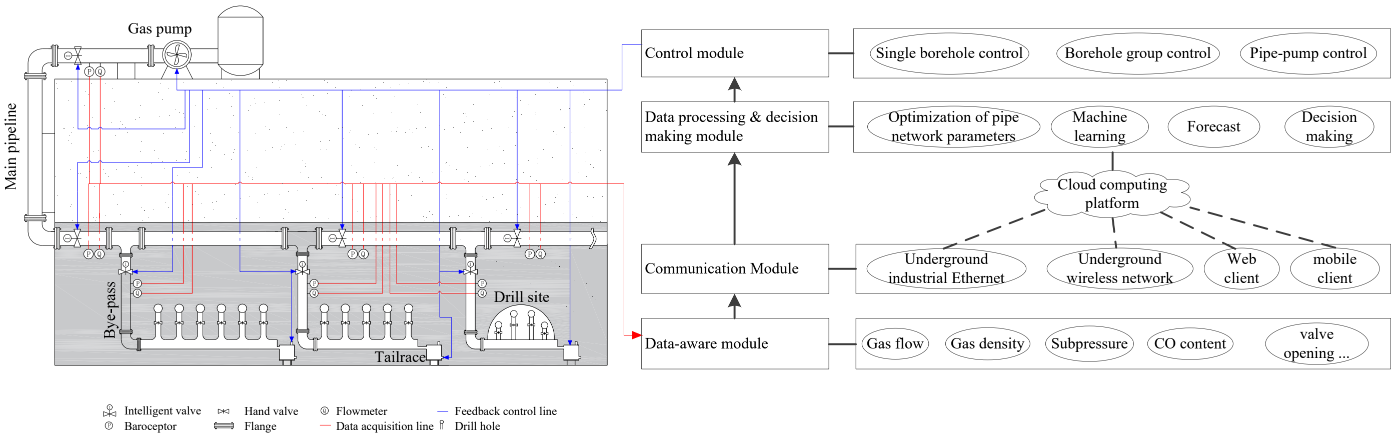

Figure 6. Diagram of intelligent gas drainage system.

The data-aware module collects gas drainage parameters by applying varied sensors or intelligent devices, and these data include gas flow, CH_4 and CO volume fractions, negative pressure, valve opening, etc.

The communication module consists of an underground wireless network, industrial Ethernet ring network, ground cloud service platform, etc. This module establishes communication between extraction subsystems and transfers the monitoring data to the data processing module.

The data-processing and decision-making module processes the monitoring data and generates an optimal gas drainage strategy.

Once the strategy has been received, the control module adjusts the working conditions of air pumps, valves, the drainer, etc.

4.2. Intelligent Coal and Gas Outburst and Rock-Burst Prevention

Rock-burst, which tends to induce substantial damage and casualties, is a common dynamic geological disaster in deep mining. Currently, the mechanism of rock-burst is still unclear; Chen (2019) introduced the three typical rock-burst prevention and control technologies [10]. A new prevention and control program was put forward based on rock-burst induced hypothesis; the technical framework is shown in Figure 7. The program consists of four modules: monitoring, data processing, early warning, and controlling.

The monitoring module is a seismic while mining observation system [42]. Microseismic signals induced by working shearer and cracked rock mass are received in real time.

The data-processing module has two major functions. The first is to identify and process microseismic signals induced by cracked rock mass. The location, original time, and strength of a microseismic event can be accurately identified through data processing, such as the picking up of P- and S-phase arrivals, source location, source parameter calculation, etc. [43,44]. The second is to identify and process microseismic signals induced by the working shearer. High-resolution velocity inversion can be conducted in real time by applying passive seismic interferometry CT. Based on the positive correlation between velocity and geo-stress, the distribution of geo-stress within the longwall panel is modeled.

According to the rock mechanics theory and rock-burst-induced hypothesis, rock failure and the geo-stress concentration are reliable indicators of rock-burst tendencies. The early warning module first identifies potential rock-burst areas, based on microseismic location and geo-stress inversion. Then the relief-drilling plan, which includes the relief area, drilling paths, and others, is scheduled.

The intelligent driller, when receiving the relief-drilling plan, will implement these instructions: repeat monitoring, data processing, and early warning modules to test the relief effect. If the detection result shows no risk of rock-burst, the system loops through the monitoring, data-processing, early warning modules. Otherwise, the system loops through early warning and controlling modules until the risk abates.

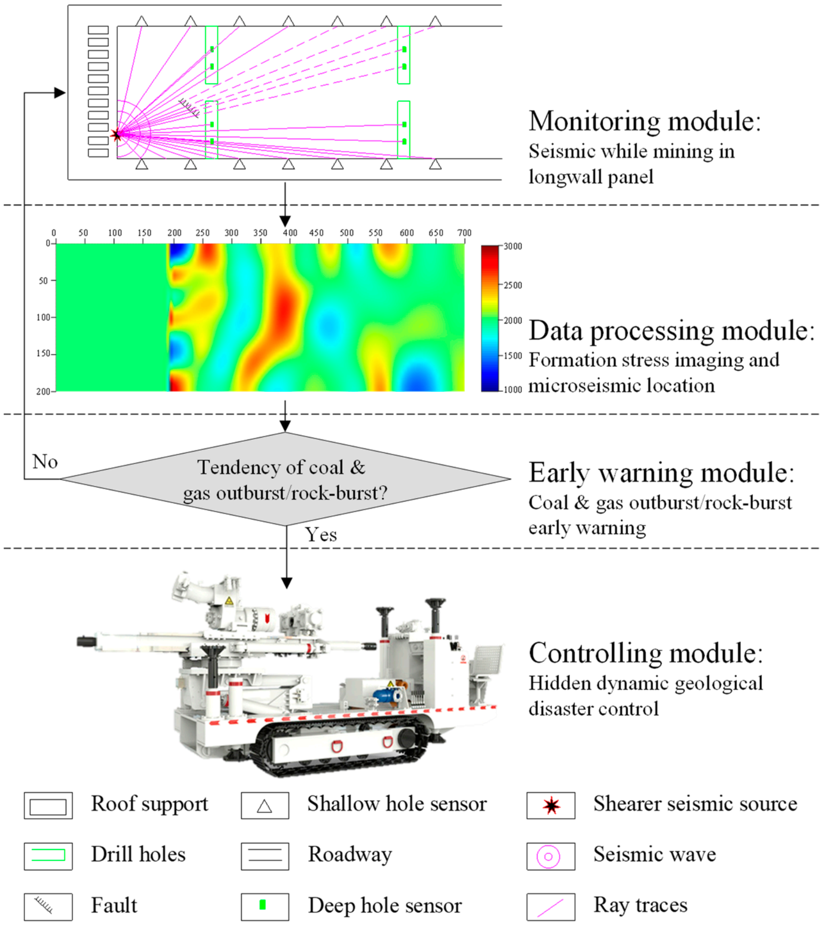

Figure 7. Intelligent prevention and control program of rock-burst.

4.3. Real-Time Monitoring of Water Diversion Fissure Zone

Due to the disturbance of initial geo-stress field induced by coal mining, lots of fracture zones are induced in coal seam roof and floor. In addition, these fracture zones tend to expand, and faults also tend to be activated. Once the fracture zones extend to concealed water-bearing and water-conducting structures, a mine water disaster occurs. Therefore, a real-time monitoring method for the water diversion fissure zone in the longwall panel was proposed based on microseismic and resistivity monitoring, as Figure 8 shows [45].

The diagram of resistivity monitoring is shown on the left side of Figure 8. The electrodes placed in the coal seam roof or floor emit or receive electrical pulses repeatedly, and monitoring substations record the resistivities between two electrodes. Then the distribution of resistivities in the coal seam roof and floor spaces can be determined through computerized tomography. The low-resistivity areas indicate water-diversion fissure zones because of the low resistivity of coal mine water. The diagram of microseismic monitoring is shown on the right side of Figure 8. The geophones placed in coal/rock seams or on the ground receive the seismic waves induced by creaked rock mass in real time. The inversion of the original time, space coordinate, and energy of a microseismic event can be conducted through data processing, which includes P- and S-phase arrival picking, source location, source parameters calculation, etc.

The risk of water inrush from the coal seam floor or roof during the mining process can be analyzed accurately by combining the mine hydrogeological condition and monitoring. Once there is a water-inrush risk, the intelligent mining operation should be stopped immediately. Meanwhile, it is necessary to implement water drainage or shutoff to ensure the safety of intelligent coal mining.

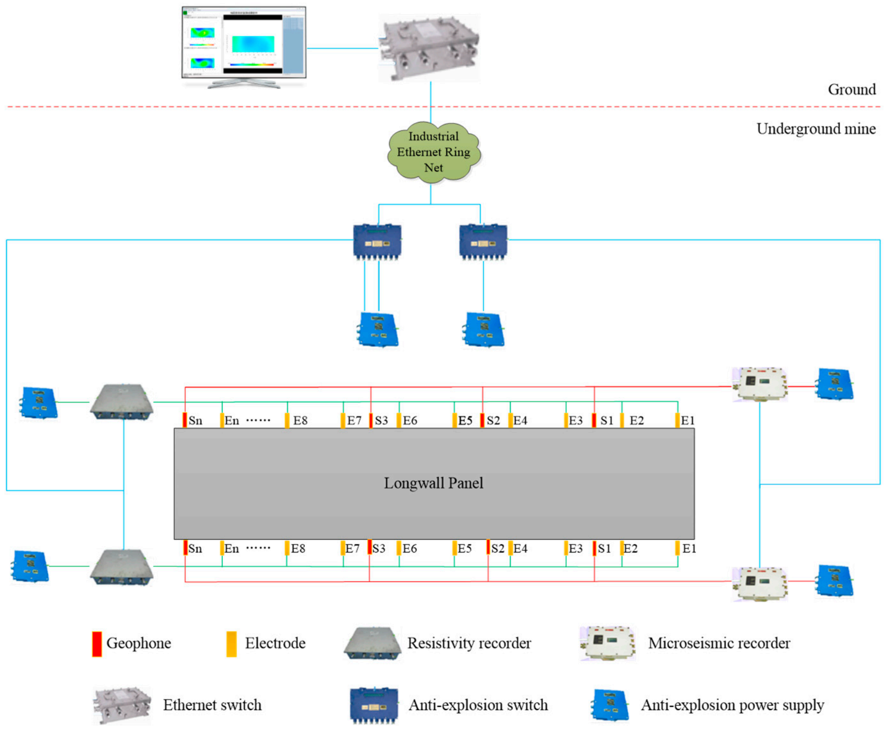

Figure 8. Topological diagram of microseismic and resistivity monitoring system in longwall panel.

5. Evaluation of the Positive Impact of Intelligent Coal Mining on Safety

5.1. Staff Organization Optimization of Coal Cutting Crew

For the coal cutting shift, the labor intensity is the highest, and the working conditions are the worst. Therefore, the staff reduction of the coal cutting shift for the intelligent longwall face is a point of focus. Table 2 shows the staff organizations of coal cutting shift of the traditional and No. 1001 intelligent longwall faces of Huangling Coal Mine [46]. The No. 1001 longwall face is the first intelligent longwall face in China, which ran successfully in May 2014.

Table 2. Staff organizations of coal cutting crew of the traditional and No. 1001 intelligent longwall faces of the Huangling Coal Mine.

Traditional Longwall Face		**Intelligent Longwall Face**	
Post	**No. of Workers**	**Post**	**No. of Workers**
Shearer operator Roof support operator	3 5	Longwall face inspector	1
Transporter, crusher operator Electrician, pump operator Belt conveyer operator	1 1 1	Controller in ground or underground centralized control center	2
Forepoling operator	8	Forepoling operator	4
Total	19		7

Compared with traditional longwall face, the total number of workers in a coal cutting shift of intelligent longwall face has been reduced from 19 to 7, dropping by more than 66%. In addition, two of the seven miners of intelligent longwall face work in the ground or underground centralized control center. The job duties of longwall face inspectors, controllers, and forepoling operators are as follows:

- The longwall face inspector patrols the integrated mining machinery through a remote-control platform which is in the intake airway. Once there are abnormal situations, the inspector issues emergency shutdowns.
- Controllers in the ground or underground centralized control center remotely control shearer and roof supports through video surveillance and other monitoring data.
- Two forepoling operators are arranged in each roadway. The workers also assist in adjusting automatic roof support movement, safety, and material recycling.

Compared with the traditional longwall face, the number of miners in the intelligent longwall face is greatly reduced, the working environment is greatly improved, and the labor intensity is greatly reduced.

5.2. Analysis of Coal Mine Safety Level Improvement

With the sustained and rapid development in intelligent coal mining technology, the coal output continues to increase, but the number of coal industry workers continues to decline, which has greatly improved the level of coal mine safety. Figure 9 shows the trends of the number of employees in large coal mines, the mortality rates per 10^6 tons of coal output, and the number of deaths from 2016 to 2021. The large mines are those with a capacity of more than 1.2 million tons. These statistics come from the Annual Report on Coal Industry Development (2016~2021) which were released by China National Coal Association [47–52].

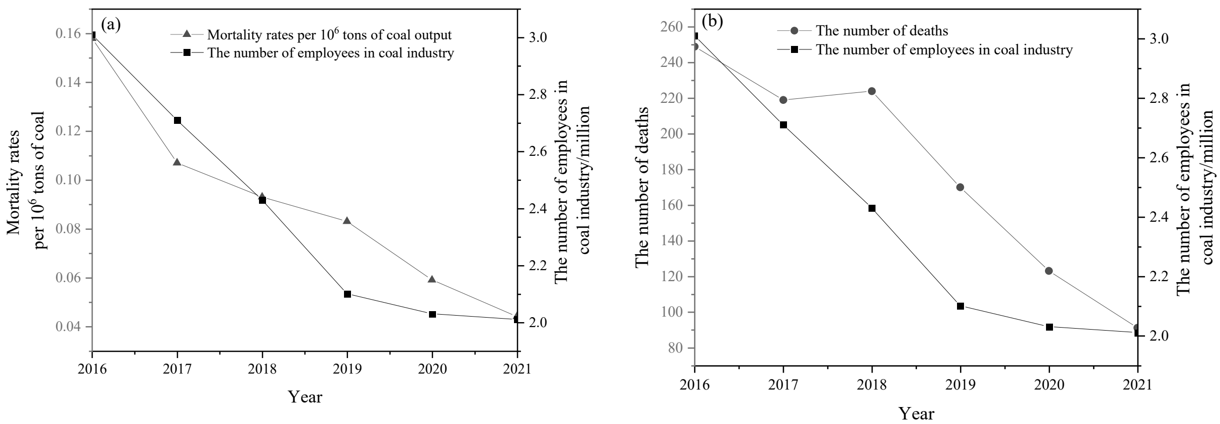

Figure 9. The trends of the numbers of employees in coal industry in large coal mines, the mortality rates per 10^6 tons of coal output (**a**), and the number of deaths (**b**) from 2016 and 2021.

In 2021, the mortality rates per 106 tons of coal output was 0.044, and the number of deaths was 178, a drop of 72.2% and 66.9%, respectively, compared to 2016. Meanwhile, the number of employees in large coal mines fell from 3.01 million in 2016 to 2.01 million in 2021, with a drop of 33%. The correlation coefficients of the number of workers in large mines with the number of deaths and the mortality rates per 10^6 tons of coal output are 0.95 and 0.93, respectively, showing a high positive correlation.

Figure 10 shows the trends of the number of intelligent longwall faces rated by the National Mine Safety Administration, the mortality rates per 10^6 tons of coal output, and the number of deaths from 2017 to 2021. The correlation coefficients of the number of intelligent longwall faces with the number of deaths and the mortality rates per 10^6 tons of coal output are -0.98 and -0.98, respectively, showing a high negative correlation. The popularization of intelligent coal mining greatly reduces the probability of casualties in the process of coal mining.

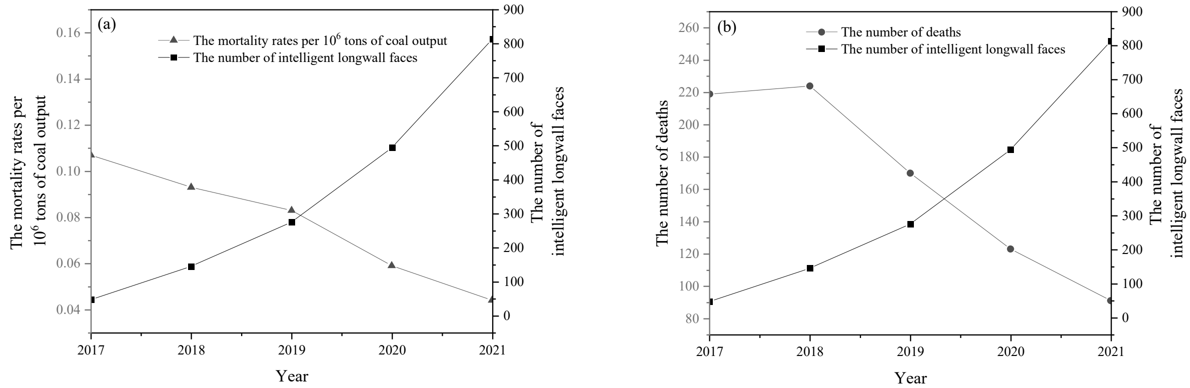

Figure 10. The trends of the numbers of intelligent longwall faces, the mortality rates per 10^6 tons of coal output (**a**), and the number of deaths (**b**) from 2017 and 2021.

The first intelligent longwall face was successfully put into operation in May 2014. Therefore, the above statistics basically reflect the positive impact of intelligent coal mining on coal mine safety. The above statistics show that the popularization of intelligent coal mining technology greatly reduced the probability of casualties in the process of coal mining in the recent years.

In the future, China will continue to push forward the supply-side reform and close or restructure the small- and medium-sized coal mines with low profit and safety levels. Meanwhile, we vigorously promote the popularization of intelligent mining technology in large- and medium-sized mines and aim at reducing the number of coal mine employees, especially the number of dangerous positions. It can be expected that the safety level of coal mines in China will continue to improve with the development of intelligent coal mining technology.

6. Conclusions

(1) Despite years of technological innovation, coal mining remains one of the most dangerous and laborious professions in China. In addition, the coal mine working condition tends to get worse due to deep coal mining. Encouragingly, the latest science and technology, especially artificial intelligence, 5G, and robotics, have brought about a revolution in the coal mining industry. Intelligent mining is expected to relieve or solve coal mine safety and health issues and ensure energy security through the combination of traditional coal mining and broader artificial intelligence. A series of policy documents related to intelligent coal mining have been issued by governments, and this drives the development of intelligent coal mining powerfully.

(2) The first-generation intelligent coal mining technology characterized by memory cutting and remote video monitoring/controlling was developed during the period of the 12th Five-Year Plan. By implementing the technology, not only was the number of miners of a coal cutting shift dramatically reduced from 20~30 to 5~7, but also most of workers were transmitted to the safe and healthy control center from the dangerous longwall face, thus improving the safety level of the coal mine. In addition, the employees in large coal mines, the mortality rates per 10^6 tons of coal output, and the number of deaths decreased by 33%, 72.2%, and 66.9% during the 13th Five-Year Plan (2016–2021), a rapid development period of intelligent mining technology.

(3) The safety conception of intelligent coal mining is "Mechanization Replacement and Automation Reduction"; that is, reduce the number of coal mine employees (especially the number of dangerous positions) by using the intelligent coal mining technology. In addition, the advanced prevention and control programs of main hazards in the longwall panel scale are also an important means to improve the safety level of the coal mine.

(4) Workless mining is the end-all solution to ensure the intrinsic safety of coal mines. While the current progresses of intelligent coal mining have been achieved mainly in shearer

automation, longwall face alignment, video monitoring, in the future, key techniques should be developed, and related management skills should be researched and practiced.

Author Contributions: Conceptualization, H.L. and X.W.; methodology, X.W.; data collection, X.W., B.W., and M.Z.; writing—original draft preparation, X.W.; writing—review and editing, H.L., B.W., and M.Z.; supervision, H.L.; funding acquisition, H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (grant U1904210, 52204175), the National Social Science Foundation of China (grant 20XGL025), the Key R&D Project of Science and Technology Department of Shaanxi Province (grant 2021SF-479), and the Science and Technology Innovation Venture Capital Special Project of Tiandi Science & Technology Co., Ltd (grant 2019-TD-ZD003, 2020-TD-ZD002).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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