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Review Article

The Encountered Problems and Solutions in the Development of Coal Mine Rescue Robot

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Based on the various problems in the process of coal robot applications, from three-dimensional analysis of the key technology, market demand, and policy regulations and standardization, the paper reviews the use of carbon fiber material, elastic material of traditional surface spraying and integral casting technology to realize lightweight robot, by using the dual redundant design to improve the reliability of the rescue robot CPU, through the functions of voice recognition obstacle sensor, gas sensor acquisition components, and distribution information to realize the underground rescue mission. In addition, virtual test technology, hardware in the loop simulation technology, and shrinkage model technology are proposed to solve the difficulties of hard field testing of rescue robots. These suggest that concrete measures have been pointed out to break the problem of the development of the coal mine relief robot.

1. Introduction

China has abundant coal resources and it is the largest coal-producing country of the world. The average depth of the mine is about 600 meters, and more than half are in the high gas area. Complex operating environment and lack of technology and management cause the fire, gas explosion, and other coal mines disasters. As Hemanth Reddy described in his article [1], "Underground mining is beset with numerous problems such as ground movement (fall of roof/sides), inundation, air blast, etc.; apart from gas explosions and dust explosions that are restricted to coal mines. Whatever may be the cause and type of accident or the extent of damage caused, it is a horrendous task for the rescue team to reach the trapped miners. The accident/irrespirable zone contains increased levels of harmful gases like carbon dioxide and carbon monoxide and explosive gases like methane apart from a deficiency of Oxygen. The entire gallery or roadway is filled with dust and smoke, or water in case of inundation, hindering the visibility of rescue personnel." How to seize the best time to implement rapid and effective rescue and how to avoid and reduce the casualties caused by secondary accidents are a hot social issue in recent years.

It has been more than ten years since the research of the mine rescue robots which were used to do the rescue work instead of human [2, 3]. The development of the rescue robot has achieved fruitful results. Great progress has been made in the key technical issues such as safety, communications, energy resources, control, lighting equipment, sensor technology, and physical design. But, so far, there is no robot capable of successfully completing the search and rescue mission. Through different cases, the author analyzes the bottlenecks in the development of the rescue robot deeply from three dimensions of market demand, policy license, and technology and puts forward some suggestions on the future development of the coal mine disaster rescue robot. The key to the development of mine disaster rescue robot is to find the problem; then the robot can be applied to the rescue work as soon as possible.

In this paper, authors have reviewed developments of the mine rescue robots and problems encountered in the past ten years. A prompt review paper on rescue robot is very useful,

Figure 1: CUMT-1, the first generation of coal mine disaster rescue robots in China University of Mining and Technology.

not only to identify the current status of research but also to provide information to anyone in the field of the rescue robot. This paper is prepared based on the development of the mine rescue robot in the past ten years.

2. Review on Development Status

The systematic review on recent development in rescue robot has been done based on sets of their application in accident.

The world's first robot of mine disaster rescue RATLER was born in 1998 in the United States, a robot with a dangerous gas sensor, an infrared camera, a gyroscope, and a radio frequency signal transceiver. But due to the laggard equipment its remote control distance was only seventy-six meters. China's first coal mine disaster rescue robot CUMT-I was developed by China University of Mining and Technology in 2006, shown in Figure 1; exploration of this robot began in 2004, which was proposed by professor Ge Shirong who created the first R&D team in China [3]. CUMT-I had basic ability of remote control, video transmission, dangerous gas detection, and moving object. But neither RATLER nor CUMT-I had been applied to the actual rescue mission because of the lack of rescue requirements.

2.1. Review on Research and Application Status Overseas. The first and the only coal mine rescue robot used in the United States is the ANDROS Wolverine, nicknamed V2 [4–6], which is designed and manufactured by Remotec Company with entrustment of MSHA. As shown in Figure 2, V2 is about 50 inches high and weighs more than 1200 pounds and is driven by rubber tracks. The rescue robot is equipped with navigation and monitoring cameras, lighting equipment, night vision, two-way voice communication, and manipulator arm. Robot V2 can be remotely operated with a distance of up to 5000 feet; the important information in the mine can be transported through the fiber optic cable; the operators can access real-time information including video and the concentration of flammable and toxic gas. In the Sago Mine disaster in 2006 [7, 8], the robot V2 was used for the first aid, but the rescue failed with moving 790 meters into the mire. This robot of MSHA is the only one robot in the mining industry in the United States. Michael Knopp [5], President of Remotec Company, seemed pessimistic on the development

Figure 2: V2 robot.

Figure 3: Robot of Western Australia Water Company.

of robots in the future; he thought the mine rescue robot had not been used deeply and widely because coal mining industry was not willing to pay for the robot; if there was no budget support, it will be difficult to develop.

Another use of the coal mine rescue robot was in the gas explosion accident at parker river mine on November 19, 2010 [9]. In the morning of 23, the rescue team sent an EOD robot into coal mine provided by New Zealand Defense Force, but it traveled only 550 m when short trouble occurred because of water in the mine after taking pictures of the mine [10–14]. In the morning of 24, the second robot was sent into the roadway for search and rescue. The third robot was a piping robot of Western Australia Water Service Company, which was designed for large pipeline operation. As shown in Figure 3, it was a robot with differential steering, equipped with camera and light and gas detection equipment and was controlled by fiber optic cable, with a maximum of 6 kilometers [14–16]. The second explosion in the 24th afternoon brought the rescue mission of the robot to an end, and all the robots were buried in abandoned alleys. In March of the following year, Western Australia Water Service Company sent another robot into the mine again; it took a lot of video data of the roadway after the explosion, to help the police to determine whether the mine can enter the recovery stage.

On February 25, 2016, near the city of Komi Republic of Russia Vorkuta [17, 18], a series of gas explosions happened in the north coal mine which was operated by Theo Kuta Mining Company; 36 people were killed. The second explosion killed all the trapped miners, including five rescue workers and one

Table 1: Robot products of Changzhou Research and Development Center with safety certification.

SN	Safety standard number	product name	Product model	End date	Safety standard number
1	MLE160001	5-explosion-proof robot device for mine.	ZR	/	normal
2	MLE160002	explosion-proof robot device for mine	ZR(A)	/	normal
3	MAB160422	The main control box of isolation and intrinsic safety robot for mine	ZR-K	/	normal

Figure 4: System of "Leader" robot.

Figure 5: CUMT-V, a coal mine disaster rescue robot with the Coal Mine Safety Certification.

miner; then the rescue stopped. On 29 February, the "leader" robots of Russian Special Force were transported to the mine; these robots were equipped with cameras, gas sensors, and other metering equipment, as shown in Figure 4. They can work in remote, dark, salt, fog, and dust areas to collect samples of air. The robot can be used to participate in the investigation instead of rescue workers to determine when to enter into the mine again [19, 20]. But the rescue only had the previous news and demonstration video of the robot; the rescue process is unknown.

2.2. Review on Research and Application Status Domestic. Domestic research and application of mine rescue robot are developing slowly. Since coal mine rescue robots CUMT-I, CUMT-III, and CUMT-III have been developed, the coal mine rescue robots from universities and units such as Beijing Institute of Technology, Shenyang Institute of Automation, Taiyuan University of Technology, and Xi'an University of Science and Technology appeared one by one. But only the CUMT-V robot developed by China University of Mining and Technology and the detection robot KQR48 developed by Tangshan Kai Cheng Group have obtained the Coal Mine Safety Certification (MA).

After two key projects of National Plan "863", "the coal mine environment detection and rescue robot system" and "development and application of the coal mine disaster rescue robot", the mine rescue robot CUMT-V developed by China University of Mining and Technology and Changzhou Scientific Research and Development Center Co., Ltd., obtained the Coal Mine Safety Certification (MA), as shown in Table 1; the end date "/" represents the certificate of safety sign of new products.

Tangshan Kai Cheng Group is the first company in China to create R&D and industrialization of coal mine disaster rescue robot, and the robot products certified by coal mine safety are shown in Table 2 [21]. Kaicheng company is also the first and only equipment manufacturer in China which obtained the Coal Mine Safety Certification (MA) and Explosion-Proof Certificates.

At present, China's coal mine rescue robot is still in the research stage of prototypes, and there are no reports of robots participating in the rescue mission.

On August 3, 2016, CUMT-V conducted an experiment of downhole rescue in Ta Shan Coal Mine of Datong Coal Mine Group, as shown in Figure 5. Three coal mine environmental detection robots were used in this experiment at Ta Shan Coal Mine, two coal mine rescue robots and a coal mine firefighting robot. The function and main performance of robots were verified, including underground walking, communication, and the successful opening of fire extinguishing equipment after the fire spot [22, 23].

2.3. Comprehensive Analysis of Development Status. Through the investigation and research above, the application status of coal mine rescue robot can be summarized as follows:

Table 2: Robot products of Kaicheng company with safety certification.

SN	Safety standard number	product name	Product model	End date	Safety standard number
1	MLE110002	Robot body.	KRZ I - BT	2020/12/1	effective
2	MLE110003	Mine robot device for mine.	KRZ I	2020/12/1	effective
3	MAJ110006	downhole robot flameproof display for mine.	KBX I - 12	2015/12/16	overdue
4	MAK120077	flameproof life detector for mine.	TBS12	2017/10/25	overdue
5	MLE120119	intrinsic safety robot for mine.	KQR24Z	/	normal
6	MLE120120	Detection robot for mine.	KQR48	/	normal
7	MAJ120275	console display of Ground output intrinsic safety robot.	KQR220Z-K	/	normal
8	MLE150001	Flameproof and intrinsically safe type underwater robot for mine.	KSJ24	/	normal
9	MLE170001	Flameproof and intrinsically safe type Inspection robot for mine.	KRXJ38	/	normal
10	MAB170513	Inspection robot device for mine.	ZRXJ127	/	normal

(1) The flame-proof design of V2 robots is in line with the relevant laws and regulations of the United States, but due to its size and hulking it was only about 790 feet in the mines and was disabled.

(2) There is flame-proof design for EOD robots of National Defense Force and a robot of Western Australia Water Service Company. The EOD robot did not take into account the humid environment, so short trouble appeared when driving 550 meters. Compared with the EOD robot, the robot of Western Australia Water Service Company has better waterproofing and sealing performance, so it entered the dangerous area. But rescue work of all two military robots and a water robot resulted in the second explosion.

In addition, a robot of Western Australia Water Service Company entered the mine disaster again in the following year for the analysis after disaster, but it was very difficult for this robot to avoid obstacles and the barrier in the narrow mine, with the adoption of four-wheel differential steering. On the other hand, its body was too heavy to be carried out, so the robot stayed in the park mine permanently after taking a lot of videos of the roadway after disaster.

(3) Russia's robots have no follow-up reports and no video data on the disaster scene.

(4) Robots have been developing steadily in China. The coal mine detection robot KQR48 developed by Tangshan Kai Cheng company and the coal mine rescue robot CUMT-V developed by China University of Mining and Technology have obtained the Coal Mine Safety Certification (MA) and obtained the permission to enter the mine, but they have not participated in the actual rescue activities yet.

So, the mine rescue robots are just of a preliminary use in the world, and at present it can only be used in very limited environment (fewer obstacles, less flooded, and short distance) and limited rescue phase. The work of rapid investigation and rescue after the accident have not achieved the desired effect. But even so the robots could be of great value to face the potential dangers of the second explosion in place of rescuers.

3. Problems and Countermeasures

Several countries have done much for the R&D of mine rescue robot in recent years, such as the United States, New Zealand, Russia, and China, with many problems appearing in this process. Then, the author will analyze these problems from three aspects of technology, policy, and market to try to find appropriate countermeasure.

3.1. The Key Technology. The improvement of technology is a very important aspect to promote the development of coal mine disaster rescue robot, especially the improvement of key technologies such as explosion-proof design, explosion-proof material, lightweight physical design, communication system [24], integration of electronic equipment, artificial

intelligence, and test methods, which are problems that must be solved in the process of practical application of coal mine disaster rescue robot.

3.1.1. New Explosion-Proof Material and Lightweight Physical Design. At present the explosion-proof enclosure of the mine rescue robot is mainly composed of iron and steel, which is very heavy. Robot V2 in the United States is 1200 pounds [4], robot CUMT-V of China University of Mining and Technology is about 500 kg, and the weight of other robots is also similar to the former according to their size and structure. The bigger the robot, the bigger the drive motor, the more the drive circuit, and the more the power battery, so it is so heavy, once insufficient, short trouble or blocking occurs, three or four rescuers cannot move it, and it is difficult to go out from the mine again. That is why those four robots in the pike mine disasters in New Zealand are lost in the mine, causing huge losses [10]. Therefore, the new structural design and the lightweight of the robot are the most important work in the field of the rescue robots [25, 26]. Molyneaux Lance proposed methods to solve the difficulties of underground mine environments; a system level design is carried out in the paper of "Development of an Underground Mine Scout Robot" [27]. To operate in an explosive atmosphere, a purge and pressurisation system is applied to a fiber glass chassis, with intrinsic safety incorporated into the sensor design. The chassis is invertible, with a low center of gravity and a roll-axis pivot. This chassis design, in combination with spoked-wheels, allows traversal of the debris and rubble of a disaster site.

The explosion-proof and lightweight design can be explored from the following three aspects.

(1) Explosion-proof design with lightweight material, like carbon fiber, glass steel, conductive plastic, and other lightweight nonmetallic materials [28]: According to GB 3836.1, the material must meet the requirements of electrostatic surface and strength [29].The spraying robot can be referenced; when part of it is made of carbon fiber material, the weight is greatly reduced.

(2) The use of surface modification techniques: For traditional lightweight materials or based on traditional craft processes, it is possible to improve the surface electrical conductivity by special technique, to avoid the surface static electricity and to improve the impact resistance, for example, the application of elastomer materials for coating treatment, such as spray polyuria elastomer [30, 31].

(3) Integrated design: Try to use the pressure casting process on the robot shell [32]. At present, many mobile phones and laptop shells are made with casting process [33, 34]; as shown in Figure 6, the ThinkPad laptop shell of the carbon fiber with integrated structure is strong [35], compact, and lightweight; in the same way, it will be very beneficial for the lightweight research of robots.

3.1.2. Integration of Electronic Equipment. (1) High integration can simplify the circuit and improve the reliability and stability. On the other hand, smaller volume and smaller weight are good for lightweight research on robots.

Figure 6: ThinkPad laptop shell of the carbon fiber with integrated structure.

(2) Reducing the number of connections by bus design: Bus design can improve the efficiency and reliability of system, and it is convenient to replace the various modules.

(3) Using reasonable heat dissipation design [36]: Due to the need of explosion-proof, the circuits are potted into a fully sealed housing; internal heat is hard to escape, so the structure should be designed to introduce the heat into the shell and try to use the shell as the cooling medium.

(4) Double redundancy design being adopted: The core device should adopt double redundancy design, especially the central processing unit, to avoid the failure of the whole robot caused by the crash [37].

3.1.3. Artificial Intelligence Specialization. The remote control is used in system for coal mine rescue robotic mainly, for several reasons [4, 15, 20, 22].

(1) Constraints of structure and security: To ensure the compliance of the requirements of the safety aspects of the design [38], many sensors cannot be applied in the mine rescue robot; for example, laser sensor and ultrasonic sensor are under strict control; robots are only equipped with cameras and dangerous gas sensors. Obviously, it is not enough for the rescue robot. It is necessary to develop special compound sensors for coal mine rescue robot to realize more rescue missions, such as intelligent navigational control and searching life signal.

(2) Rugged environment: The mine environment underground is extremely bad, dark, damp, dust, and black background, as shown in Figure 7. The camera is the most important sensor of remote control robot; it is difficult to learn and analyze of the image information extracted by the camera in this environment with artificial intelligence algorithm. It can only be controlled by artificial remote control [39, 40], and the robot will lose the capability of operation once it is separated from the remote control, and the rescue mission will fail.

(3) The unstructured environment of coal mines: At present, the artificial intelligence algorithm is still in primary stage; it can perform navigation work better in the structured environment compared to the unstructured environment.

Based on the above three reasons, navigation technology in the field of traditional robot research is difficult to be

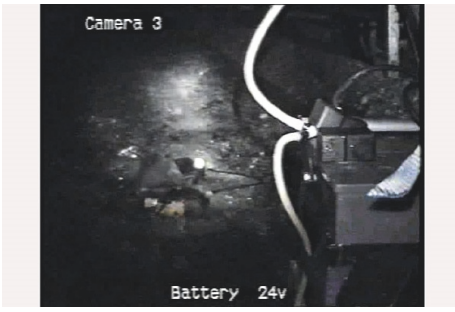

Figure 7: Mod robot and photos taken in environment of mine disaster.

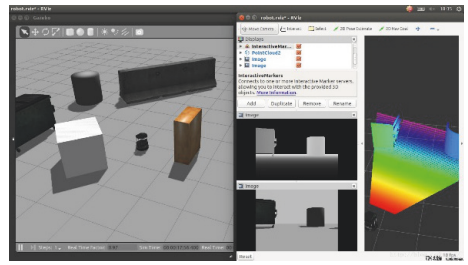

Figure 8: Virtual test of robot Gazebo.

applied in the coal mine rescue robot, but other artificial intelligence technologies following can be cited:

(1) Recognition and analysis of speech information [41, 42]: The robot can recognize all kinds of voice correctly by intelligent identification system and to judge the direction based on these signals, such as signal for help, including the human voice, tapping, and explosion under the noise environment of coal mine disasters.

(2) Image enhancement and obstacle recognition: The image in bad environment can be denoised and enhanced automatically so that the operator can identify or judge the surrounding environment, such as the distribution of obstacles. The ability of intelligent identification and measurement of the underground obstacles can assist the operator to make decisions about the obstacle avoidance of the robot [43–45].

(3) Analysis and identification of dangerous gas components [46]: Use modular gas sensors for recording the distribution and analysis of the gas components to identify the robot's environment risk. It can assist robot operator in judging robot environment risk in order to make the right judgment.

(4) Position navigation based on image features: According to the analysis of the position of the robot and determination of various borehole geometry, image characteristics in the environment after disaster, such as various kinds of markers, sign recognition vision system of robot, the operator can make an accurate navigation judgment.

3.1.4. Test Method and R&D Method. Like all other mechanical and electrical products, the R&D of the mine rescue robot cannot be apart from the development of the test methods. As a special robot, the opportunities of taking part in the rescue are few; in these conditions, how to carry out the test and development? The following methods can be used to help the robot to adapt to the environment in the disaster areas better.

(1) Virtual Test Technology. There are three types of virtual tests currently. The first is virtual testing technology based on virtual instrument and software, such as Labview. The second is the virtual testing technology based on software simulation [47, 48], software like Ansys, RecurDyn, Matlab, etc. The third is virtual reality based on virtual testing technology. A robot physical model similar to real robot is simulated in the computer. The robot can be controlled and operated with control programs running on the model of the robot, like Evolution Robotics ERSP, Microsoft Robotics Studio, OROCOS, Skilligent, URBI, Webots, Player, Stage, Gazebo, iRobot AWARE, Open JAUS, CLARAty, V-REP, Unity3D, and so on. Currently, there is virtual test of robot Gazebo, which is an important component of ROS in robot operating system, as shown in Figure 8. These tests can be used to test the functionality, maneuverability, and robustness of coal mine rescue robots.

(2) Semiactual Object Simulation Test. The semiactual object simulation is a technique of testing with connecting the object with the simulation model (such as mathematical simulation) on the computer [49–52]. The semiactual object simulation system of the driving system is shown in Figure 9. It is difficult to test with a real machine in a harsh environment where the mine rescue robot works; three coordinate test machines (temperature, humidity, and vibration) can be used to simulate the bad environment underground; combined with the virtual test of robot control system, the robot is simulated with semi-physical simulation to test the reliability of the robot controller and functionality.

(3) Test of Scaling Model. Test of scale model is mainly used in the case that the real machine cannot carry out the test or due to the larger cost of the experiment. For example, wind tunnel test of scale model can be used in the coal mine rescue robot with flying function; for EMC test of some large robots, the scale model can also be used [53].

(4) Iterative Development. Iterative development is generally used for development of systemic engineering, often found in the development of software [54, 55]. This method decomposes the entire development work into a series of short, fixed-length projects; each iteration includes the entire process from definition and requirement analysis to design, implementation, and testing. This method can simplify the complex problems gradually to refine the requirements according to the customer feedback, to improve the whole project solution through the iterative process continuously. The iterative development is shown in Figure 10. The product and development of coal mine rescue robot are complex systematic projects, which integrate the technology of machine, electricity, and software. At the beginning of the design, this work should be divided into many independent development units for independent development, like the drive unit, driving mechanism, control software, video transmission,

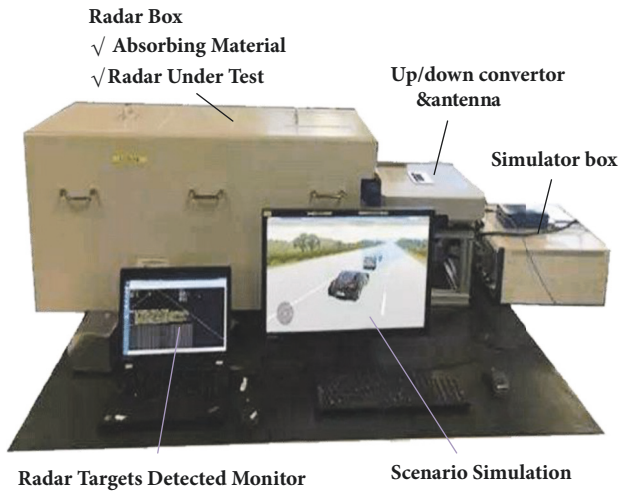

Figure 9: The semiactual object simulation system of the driving system.

etc., and then each unit is divided into several development stages again, like the interface design of drive unit, driver design, embedded software design, motor driver test, load test, and so on; each small project should also continue to iterate and improve and divide complex problems into small problems, to improve the entire life cycle of robot products step by step [56].

3.2. Standardization Problems

3.2.1. Security Permissions. The working environment of coal mine underground is special, and the environment after disaster is more complex, so the rescue work can be done only with permit of this industry. Robot and then how to obtain the franchise for the rescue work underground are the most confusing problems which have to be faced for every researchers of mine rescue robot.

The coal mine is strict with safety requirements for electrical equipment entering the mine [57, 58]; explosion-proof electrical equipment should be checked, with "the product certification", "the mining products safety approval", "the flame-proof certification", and safety performance before entering the mine; the flame-proof certification is issued by the qualified testing institution, and the mining products safety approval shall be issued by the national center for the safety of mineral products (the office of safety marks of mine products) [59]. It will take a long time with the process of testing and certification for the mine rescue robot before entering the coal mine. According to GB3836 standards stating that "the explosion environment is guarded against bursting the electrical equipment"[29] and international standards of IEC 60079 "electrical equipment used in explosive gas environment"[59], the safety problems of various components of coal mine rescue robot are analyzed and the corresponding suggestions are put forward in literature [47].

In order to solve problems of licensing issue of mine rescue robot, many enterprises put forward many measures; as mentioned earlier, Changzhou Research and Development Center Co., Ltd., and CITIC Heavy Industries Kaicheng Intelligent Equipment Company have adopted the new product safety sign certification prototype for their robot products, end date "/" in Tables 1 and 2, identified as security certificate for the new product; the "scope" of its "certification product details" says "this certificate is the new product safety certificate. it has certain limitation if just on the basis of the existing common standards and specifications for the product safety performance evaluation, there may be unknown risks, the holder should guide users to use and maintain correctly, to ensure the product used safely". In addition, regulations emphasize the certificate of quantity and number of the following products. But this method applies only to a limited number of new products and is not suitable for mass production.

3.2.2. Inspection, Evaluation, and Standardization. We must have a series of quality assurance measures, including the inspection, evaluation, and standardization of the quality of the robot products to promote the use of robots [60, 61].

The Ministry of Industry and Information Technology has been ahead in the inspection and evaluation of robots. The National Robot Detection and Assessment Center of National Development and Reform Commission has been approved and locates in Beijing. The establishing and operation of this public technology service platform are in the charge of China software center which can provide public technical service for robot industry [59, 62], and this platform has by approved by National Intelligent Robot Quality Supervision Test Center and Product Certification of Mechanical Equipment and Parts. Then, the Robot Detection and Evaluation Center is established in Shanghai, Chongqing, Guangzhou, and other regions.

Relative researches standardization works are now carried on actively by Standardization Working Group of special type of working robot in our country [63]. In July 2017, general technical requirements of robot for the ground search and rescue were launched; further testing, evaluation, and certification system would follow up with the development of standard work. It is believed that the coal mine disaster rescue robot will obtain the legal basis of entering the mine quickly with further advancement of standardization work.

3.2.3. Policies and Regulations. The ownership and underground operation of the coal mine rescue robots must be based on policies and regulations, for example, the method for the extraction and use of enterprise safe production costs [64–66]; this regulation was issued by the Treasury and the State Administration of Work Safety (SAWS); the coal production enterprises must improve the six systems spending, such as monitoring and control system for coal mine, personnel location system, emergency aversion, forced air self-help, communication, and avoiding, expenses for emergency rescue equipment communication, facility layout, and maintenance, and expenses for emergency evacuation and emergency shelter equipment configuration and emergency drill; the coal mine disaster rescue robot can be paid according to the underground detection and monitoring,

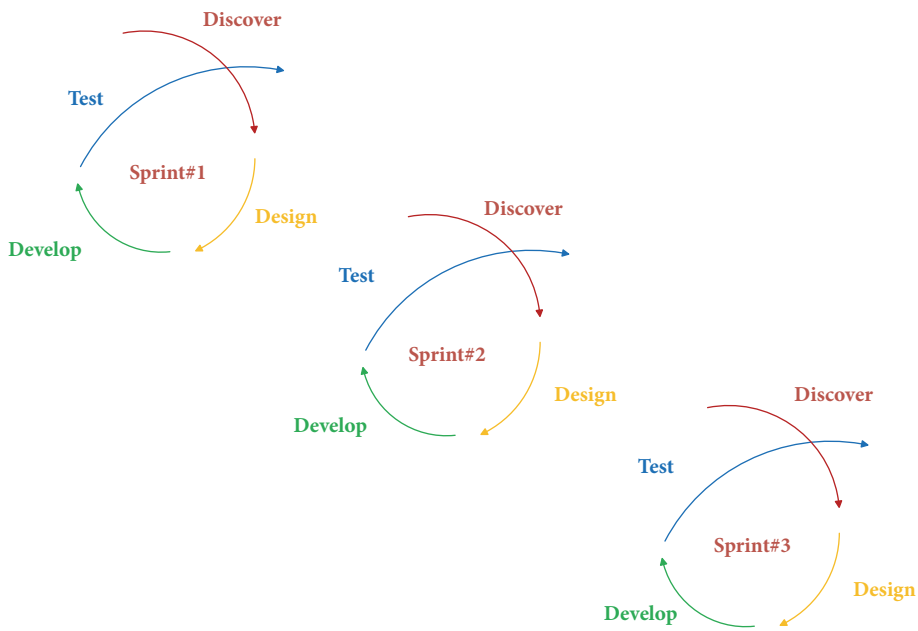

Figure 10: The iterative development.

communication and safety, emergency rescue technical equipment, and other items.

According to the safety regulations, such as the principle of classification explosive dangerous places, the mine explosion-proof electric locomotive must be cut off when the gas concentration exceeds 0.5%. It seems that current standards and specifications make it impossible for coal mine rescue robots to work underground. Literature [29] proposed that equipment of explosion-proof and intrinsic safety can be used for disaster rescue robot and improve the safety performance of the robot by the high-performance materials and special structure design, trying to solve the policy problem of mine disaster rescue robot from the standard and legal level.

It is worth mentioning that the relevant standards of spray painting robots have a great impact on the application of robots [67–70]. The environment is where spray painting work is poisonous, so the spraying robot is widely used in industry. During spraying, volatile organics (such as acetone, toluene, xylene, and ethyl ether) in the airtight room of spraying can form explosive environment. The explosive gas environment in the paint area is Level 1 danger zone area [71]. Due to the long term in the explosive gas environment, the spray painting robot work is dangerous similar to the work of the coal mine rescue robot. Nearly 30 years after multiple versions of revision to ensure that the spraying robot is able to be used under the special working environment, it provides a clear legal protection for robot manufacturer; it also provides a good demonstration effect for mine rescue robot.

According to literature [72], the cause of secondary gas explosion of coal mine is more complex [73], mainly because of the state of the coal mine disaster (comprehensive reasons, complicated reasons). It is impossible to prevent. Robots are not the major factor. Explosion-proof design is necessary [74, 75], but if grade of explosion-proof is overemphasized too much, it will be contrary to the original intention of the robot. The most important function of the coal mine disaster rescue robot is to collect the gas composition of the environment in the mine after the disaster and provide accurate analysis result to help the rescue workers in the background to make the correct judgment and decide whether to send rescue workers into mine to carry out rescue work; its effect is to reduce casualties in the process of rescue.

The excessive explosion-proof design will make the robot a huge volume and weight burden, which will bring a series of problems, like slow moving speed, poor ability of obstacle, short distance of operation, short battery life, etc.; these problems will make the robot unable to complete the detection and rescue mission. It is hoped that the relevant departments will give special regulations for the coal mine disaster rescue robot, so that this technology can truly benefit the mine and the vast coal mine workers.

3.3. Market Analysis and Recommendations

3.3.1. Analysis in Demand Side. The occurrence of coal mine disaster is not the normal event of coal mine, the use of the robot is seldom, and the iteration speed of R&D is bound to be affected by the frequency of use. In addition, the situation of the disaster is very different each time, which makes a great affection to the simulation experiment of the rescue robot. So even in the United States, where technology of robots is advanced, the development of coal mine rescue robots is very slow. Remotec is pessimistic about the market of coal mine rescue robots. The author holds that abnormal coal mine accidents caused the discontinuity of the market demand, which influence the development of robot's market.

The mine disaster is a threat to the safety of life and property of the broad masses of the people; once it occurs, the death toll is large and the impact is enormous; therefore, we

Figure 11: CITIC Kaicheng's firefighting robot.

should formulate policies actively to guide the demand of coal mining enterprises. On the other hand, with the development of The Times, people's demands for life safety and work environment are getting higher and higher; in addition to coal rescue robots, coal mining work robots will be used more and more to replace people in harsh environments [76, 77]; this growth in demand will be enough to drive demand for coal mine rescue robots.

3.3.2. Analysis in Purchasers. There are many robots with explosion-proof technology being used in the field of production, the use frequency of robots in the field of productive is very high, and the extensive use makes the technology of robots develop rapidly, like the firefighting robot, the spray paint robot (request explosion-proof), and so on. CITIC Heavy Industries has the whole product series of the firefighting robot. As shown in Figure 11, the fire robot series has succeeded in business, as the buyers are just the local governments. Similarly, the authors think the mine rescue robots will achieve success if the buyers are the new coal mining enterprise or the group with robot operation that can respond to the disaster quickly with the corresponding talent and the equipment support. It is beneficial for the rescue robot to play the biggest role.

3.3.3. Analysis in Operators and User. Like other robot products, the coal mine rescue robots need specialized teams for maintenance, training the operators, and calibrating the sensor regularly [78]. Therefore, the user of the rescue robot needs to establish a professional team to meet these needs. But for a coal mine it is difficult to establish such a professional team. It is more reasonable to build a robot rescue team based on the area since coal mining enterprises are relatively concentrated in one area. So the coalmine groups of the same area should adopt the form of cooperation; also, they can cooperate with the safety supervision, firefighting, and even specialized rescue companies to achieve the complete operation team of rescue robot.

4. Conclusion and Prospect

This review summarized existing problems and limitations of rescue robots in order to develop a reliable and practical mine rescue robot.

In conclusion, though a great deal of effort and practice have been done, there is still no successful case of rescue robots completing the rescue mission in the world. The scope of this paper has not been discussed in available review papers. The work remains a hard problem in the world; the bottleneck of this problem is not only about technology, but also related to market demand, policy license, and many other reasons. In this paper, the analysis is done from the theory and practice dimensions in the hope of attracting universal attention. The government support and the construction of legal system will ensure the achievement quickly and also will make enterprises and organizations have enough confidence in further research and development work, to promote the development of mine rescue robots faster and then realize the industrialization as soon as possible. The author hopes that the rescue robot can be applied to the underground rescue work early and successfully.

Data Availability

The authors declare that the data supporting the findings of this study are available within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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