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Evolution of applicability of robotics in underground mine services

Mining is one of the most hazardous and hostile occupations in the world. Even though a lot of hazards are associated with this industry, mining of both fuel and mineral based deposit from earth is necessary for the economic growth of the nation, maintaining a low cost of production by avoiding import and gaining independence from other mineral rich and technologically advanced nation for its day to day requirements of minerals. But, the industry must keep in mind that it should adopt the policy of safety first than production in the context of a large number of dangers which are associated with mining activity and must take necessary action to avoid such unwanted events from happening. Though safety standards in current mining industry scenario have improved by providing training sessions to miners regarding safe and better work practices and using better machines for stabilization of mining structure and extraction. But still disaster tends to happen in mines worldwide and rescue of miners and mining machinery is the first task that is performed by industry by sending rescue team without prior knowledge about underground mine environmental condition since post-disaster installed mine environment monitoring is either damaged or destroyed. Subsequently, sending mine rescuers will be dangerous and may cause even bigger disaster from happening which is evident in past. Therefore, the mining industry is now relying upon robotics for mine disaster rescue management to assist human rescuers and avoid further exposure to dangerous post-disaster underground mine environment. This paper gives an overview of applicability of robotics in mine disaster rescue management.

Keywords: *Robotics, WSN, RFID, underground mines.*

I. Introduction

Mining industries in India is severely affected by roof fall, mine fire, explosion due to gases and inundation [1-2]. Roof falls are mainly taken place due to gradual worsening of strata in an unpredictable way due to stress redistribution during the extraction process. Sudden fall in the working area due to lack of proper support and overriding has claimed the life of many miners. Underground coal mine gas explosion is another alarming disaster that caused a lot of casualties. Gas is liberated during the process of extraction of coal due to its inherent properties. Though ventilation system dilutes the concentration of gases, sometimes the accumulation of CH_4 takes place due to the inefficient ventilation resulting in explosion within its certain range [3-4]. Sudden inrush of water due to improper geological survey invites water logging during mining activities and claims loss of lives and assets [2].

In view of these facts, several technologies for mine safety have been developed to minimize the hazard and improvise the mine working environment. But, still, a large number of mine disasters are taking place in Indian underground coal mines. Figs.1 and 2 depict the cause wise analysis of fatal accidents and miners killed in underground coal mines respectively, during the last century (1901-2007) [5]. It clearly indicates the need of deployment of more advanced technologies such as robotics to prevent the fatal accidents and efficient post disaster rescue operation and elimination of post-disaster risk. There is an urgent need to search for suitable technological options in this area of concern. Therefore, in the present paper, an overview of various applications of robotics for prevention and rescue of mine disaster has been discussed including some case studies.

II. Design requirement of mining robots

It is a well-known fact that any electronic/electrical equipment needs intrinsic safety/flame proof certification for underground use to maintain safe work environment. It keeps away the probability of occurrence of any undesirable event associated with explosion due to spark/flame. Since the robot is a mechatronic system, i.e., a junction where concepts from mechanical engineering, electrical engineering, and computer science are merged to design, build and operate products. Therefore, it requires fulfilling the norms laid down for the electrical equipment to be used in hazardous areas like coal mines. However, no such stringent restrictions are applicable in the case of metalliferous mines. Based on the different

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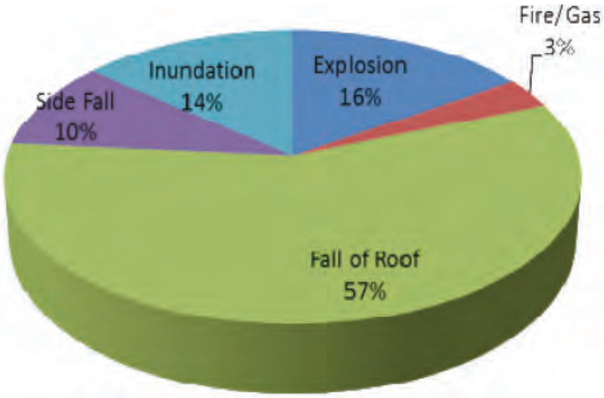

Fig.1 Fatal accidents in Indian underground coal mines (1901-2007)

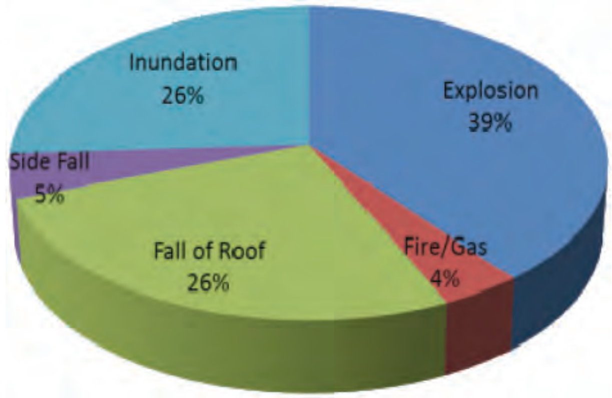

Fig.2 Person killed in Indian underground coal mines (1901-2007)

activities carried out during disaster in underground mines, for example (i) post disaster environmental monitoring, (ii) debris removal from galleries after roof or side falls, (iii) medical assistance to victims after disaster etc., the following additional features are required to be incorporated in the design of such systems for speedy and efficient rescue [6], such as (i) camera with full degree of rotation along multi-axis, (ii) zooming capability with LED based illumination for low light photography, (iii) real time gas sampling and monitoring, (iv) ability to perform both inspection and rescue operation, (v) sufficient payload carrying capacity, (vi) wireless control to avoid disruption in transmission, (vii) self-powered, (viii) high degree of drivability and adaptability in rough terrains, (ix), ability to operate in high operating temperature, (x) ability to traverse through confined spaces, (xi) ability to detect survivors in sites using thermal camera and sensors, and (xii) ability to carry sufficient amount of life relieving equipment and food supplies.

There are many design and application based requirements for mine disaster rescue management robots which mainly depend upon the types of mines in which it is to be operated in case of disaster i.e., coal or metalliferous mine and type of task to be performed which is completely dependent on areas of applicability.

III. Technological advancements in mine rescue robotics

A number of mine rescue robots using different technologies have been developed worldwide which may be categorised as single robotic system (SRS) and multi robotic system (MRS). But, such technologies too need some assistance in terms of closed loop feedback system for its efficient operation in underground mines.

In order to facilitate such assistance, the wireless communication system may be an opportunity to introduce with different robotics systems to make the mine completely automated and mechanized. Till date, such technologies are used in SRS based systems as discussed below.

A. Wireless sensor networks using Zigbee technology

ZigBee technology provides a huge opportunity for tracking and tracing the miners and monitoring the underground environmental parameters for enhanced safety and productivity [7-8]. This technology can also be integrated with the mine rescue robots equipped with strategic gas sensors for monitoring CO, CH_4 and other hydrocarbon based gases. Received signal strength index (RSSI) variation from ZigBee nodes can be used as a tool to determine the location of explosion [9]. RSSI values vary inversely with the underground temperature. It is obvious that temperature will increase gradually before explosion resulting decrement in RSSI value. Therefore, this characteristic behaviour of Zigbee can be utilized as autonomous guidance and navigation system [10]. The prototype design is represented in Fig.3.

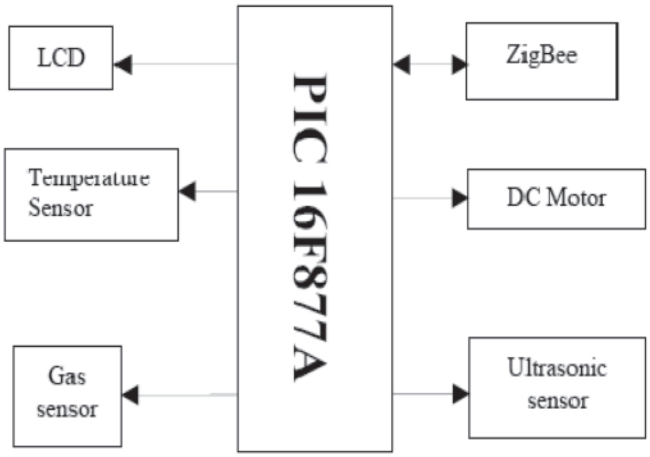

Fig.3 Robot block diagram using ZigBee technology [9]

B. Enhanced radio frequency identification (RFID) based disaster management

Tracking and identification of miners trapped in underground mines without knowing exact location is a nightmare for mine disaster rescue management. Therefore, various systems based on RFID have been designed for disaster management [11-12], for example, wireless information and safety system (WISS) for tracking and tracing the miners [7], object position tracking [13] and mapping and localization [14]. These systems can be integrated with the mobile robots fitted with onboard reader unit which will facilitate the robot for more applications. The advantage of onboard reader unit is that the robot can travel into non-approachable sites in case of underground coal mines.

C. SRS MINING ROBOTS

Some of the SRS robots developed for usage in underground mines for disaster management have been discussed below:

1. NUMBAT robot

It was developed in the early 1990s by CSIRO Australia as shown in Fig. 4, for underground mine surveillance under the category of surface/incline entry type for the purpose of carrying out mine inspection visually and analysis of mine air samples [15]. It has carried out the survey for a number of underground mines in Queensland, New South Wales and Victoria. It is essentially a low speed eight wheeled drive based mine search and rescue robot operated using graphic user interface (GUI) and an optical fibre for transmission of a command from operator side. The enclosure is ingress protected and N_2 gas pressurized to avoid the possibility of post-disaster accidents due to fire [6, 16-17].

Fig.4 NUMBAT [6]

Fig.5 Ground hog [18]

2. Ground hog robot

It was developed in the year 2003-05 by Carnegie Mellon University (CMU) as shown in Fig.5 which was initially used for the purpose of carrying out map generation of abandoned underground coal mines [17]. The design was based on four wheeled drive traction system relatively smaller than a golf cart. However, the system lacks in terms of cross-ability and drivability in even in the slightly uneven terrain of underground coal mine [18].

Fig.6 Wolverine robot [16]

3. Remotec Wolverine robot

It was developed by the Mine Safety and Health Administration (MSHA) under the category of surface/incline entry (Fig.6) and deployed in seven underground mines for the purpose of carrying out two rescues and three mine recovery operations. Earlier, the system was manually operated. In view of this, a modified version of the same has been designed which is optical fibre based teleoperated system [19]. However, the system lacks to function satisfactorily due to damage of optical fibre because of the fall of the chunks from the unstable strata, over-driving of the robot during return phase in terms of fibre length and frictional abrasion between mine floor and optical fibre.

4. Gemini scout

It was designed by Sandia National Laboratories, USA (Fig. 7). Since it was developed for deployment in specific coal mines, therefore, the dimensional parameters were restricted to two feet height and four feet length [20]. The system is intrinsically safe and ingress protected and can be used in hazardous areas. The system is equipped with wireless

Fig.7 Gemini scout [6]

communication devices on 2.4 GHz and 900 MHz. The degree of drivability has been improved in the system by introduction of articulated body and rubber based crawler tracks [16-17].

5. UKZN constructible arm elevating search and rescue (CAESAR)

It was developed by University of Kwa-Zulu Natal's, Taiwan (Fig. 8) and basically used for underground mine fire fighting. It operates based on artificial intelligence technique for detection of the undesirable event and survivors/victims using gas and digital image processing [6, 21-22].

D. MRS MINING ROBOTS

Shortcomings of SRS can be eliminated by the introduction of artifical intelligence (AI) and ant colonization model to facilitate cooperative behaviour with multi-purpose utility robotic system. AI based decision-making system may be an opportunity to introduce with different robotics systems to make the mine completely automated and mechanized. Till date, these technologies are used in MRS. Some of the MRS with these technologies are discussed below.

Fig.8 UKZN CAESAR [6]

1. Autonomous multi-robot with cooperative behavioural model

Robots with multi-robotic systems (MRS) use multiple robots which are connected wirelessly to each other to perform specific tasks. These robots work with cooperative behaviour i.e. the task performed by an individual at a particular site would not be repeated by the other robots at the same site. Figs.9 and 10 illustrate rock fall inspection and monitoring of underground mine gases by MRS, respectively [23]. The advantages of MRS are (i) performing decision making task such as defined activities to be performed by onboard sensors, (ii) transmission of underground data such as percentage/composition of mine gases and ground control parameters, (iii) registering the location of inspected site in database and conveying to other robots to avoid repeatability of the performed task [16].

Fig.9 Robots inspecting for rock falls in an underground mine while communicating [23]

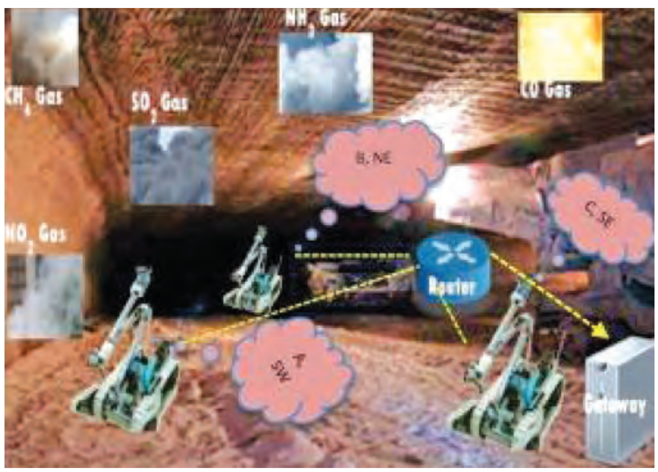

Fig.10 Robots inspecting for level of gases in underground mine while communicating [23]

2. Disastrous emergency response robot team technology

In order to facilitate cooperative model in mine disaster rescue operation, Law et al. [24] proposed a cooperative rescue robot system, called disastrous emergency response robot team (DERRT) for unmanned mine rescue operations. The system is composed of a group of robots. Each robot is equipped with different on-board equipment for (i) coordinating the task (coordinator), (ii) debris removal (crusher), (iii) providing temporary stability to mine structure (lifter), and (iv) medical assistance to victims (saver). DERRT is having multi-purpose robots performing different tasks in the cooperative based model. However, limitation does exist in the system, for example: (i) deviation from the desired task due to inefficient coordination, (ii) absence of multi utility tools for the proper functioning of the task, (iii) absence of self-sacrificial design for a support system and (iv) insufficient capacity of saver's storage tank. Therefore, these features may be included to the system for the efficient rescue operation. This would help the mine management to conduct unmanned mine rescue operation efficiently and timely without losing more lives trapped during a disaster. It would also help to save the rescuers' lives from any post disaster activities.

IV. Conclusions

In the present paper, an overview of various technological advancements in the field of mine disaster rescue management using robotics along with various assisting technologies has been discussed to perform the different tasks. Initially, single robot system (SRS) based all-terrain vehicles (ATV) was used for monitoring of the post-disaster environment and transmitting data regarding the degree of vulnerability to mine management. As the technology advances, various assisting techniques were introduced to the SRS such as wireless sensor networks based on ZigBee and RFID based sensor networking technologies. Due to lack of efficiency in SRS, MRS has been introduced based on the cooperative behavioural model, artificial intelligence, swarm intelligence (ant colonization) etc. However, MRS involves a huge investment in comparison with SRS based technologies. Till date, single or multi-purpose ATVs based robot assisted by static multi point sensory network has been employed which are either human operated or autonomous. However, design lags behind in terms of degree of flexibility in movement in rough terrain and usage of a large number of static multi-point communication devices/sensors which add to the operating cost. Therefore, there exists a need to develop flexible single point sensory device for early detection of disaster symptoms based on obstacle free traction system.

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(Continued on page 198)