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Development of underground mine monitoring and communication system integrated ZigBee and GIS

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ABSTRACT

An automated underground mine monitoring and communication system based on the integration of new technologies is introduced to promote safety and health, operational management and cost-effectiveness. The proposed system integration considering Wireless Sensor Network (WSN) assisted Geographic Information System (GIS) enables to monitor and control underground mining applications from surface office. Based on the capabilities of WSNs, ZigBee network is adapted for near real-time monitoring, ventilation system control and emergency communication in underground mine. ZigBee nodes were developed to sense environmental attributes such as temperature, humidity and gases concentration; switching ON and OFF ventilation fans; and texting emergency messages. A trigger action plan for monitored attributes above normal and threshold value limits is programmed in the surface GIS management server. It is designed to turn the auxiliary fans on remotely or automatically in orange condition and sending evacuation messages for underground miners in unsafe (red) condition. Multi-users operation and 3D visualisations are other successful achievements of the proposed system for the underground monitoring and communication.

1. Introduction

Underground mine safety and health remain challenging issues in the mining industry. Death toll statistics in China's coal mines have gradually reduced from 5798 to 2631 between 2000 and 2009 but fatality still occurs [1]. The number of occupational mining fatalities in the United States' underground metal mines has fluctuated from 40 to 46 during the years 2001–2010. Most importantly, 33.8% of the deaths have resulted from ignitions and explosions of gas or dust in underground mining [2]. In April 2014, two men were killed when a wall collapsed in an underground coal mine in New South Wales, Australia. Human errors were concluded from reports as the most significant reasons for mining fatalities. Thus, safety is always a significant concern in mining operation. Some studies have recently focused on improving the health for underground miners. Laney and Attfield have drawn attention to the fact that the prevalence of coal workers' pneumoconiosis or progressive massive fibrosis increased from 1990 to 2000 among United States underground miners [3]. Therefore, specific consideration of both safety and health issues deserves priority in mine operation management and engineering designs to provide and maintain a safe and healthy workplace. In response to these challenges, mine automation by new technologies such as Wireless Sensor Network (WSN) assisted with geographic information system (GIS) has been widely utilised in underground mines to enhance safety and health, productivity and reduce operational costs [4,5].

The underground WSNs consist of a few to several hundred nodes between a surface gateway and specified sensor nodes at underground levels [6]. ZigBee based on IEEE 802.15.4 protocol is a new wireless sensor technology which has more benefits than other WSNs for underground monitoring and communication systems [7]. Even though ZigBee technology provides only a low data rate, its benefits are low power consumption, very cost-effective nodes, network installation and maintenance [8]. It is also capable of providing networking applications for data transmission between nodes (node to node relays) with high performance based

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on many wireless hops. It does not require any access point or central node to transmit data between clusters. Significance of ZigBee in underground mines compared to other WSNs was evaluated in the recent publication of authors [9].

GIS is new technology used for spatial data analysis in order to capture, store, analyse, manage, and present data that is linked to locations [10]. GIS allows users to view, understand, question, interpret, and visualize data in many ways that reveal relationships, patterns, and trends in the form of maps, globes, reports, and charts. Web-GIS is an inevitable trend which helps solve the problems of spatial information integration and sharing in technical aspect of web media [11,12]. Recently, researchers have technically focused on the GIS supports for the management of emergency and unsafe conditions [13–16].

In this study underground safety and health concerns are significantly mitigated based on the system integration which incorporates ventilation management and emergency message texting. The system integration based on the development of ZigBee nodes is introduced to sense the underground mine environment, to regulate ventilation system and to communicate between surface offices and miners. Therefore, reduced power consumption, near real-time monitoring of the environment and bilateral communicating between surface and underground personnel are achieved. Experimental tests were carried out to verify network reliability and security of the packet delivery in underground mines. The architecture of underground monitoring and communication for the system integration is illustrated in Fig. 1. Temporal ZigBee data including messages and environmental attribute readings such as temperature, humidity and gases concentration are transferred to GIS management server in the surface control centre. The transmitted data are received and stored by ZigBee program then provided for manipulation in the control centre. Risk situations are immediately identified and responded through a logical process of data analysis in the GIS management server before reaching dangerous (unsafe) levels and accidents occurring. The ventilation system management is also used for the workplace health and safety compliance and the optimisation of mine site power usage.

The remainder of this paper is organised as follows. The fundamental knowledge of ZigBee technology and GIS are first described. Then, the implementation and structure of system integration are demonstrated. Finally, the strategic process of combining ZigBee data and map information through the GIS management server is modelled for monitoring, communication and controlling the environmental attributes in an underground mine.

2. Background of ZigBee and GIS system integration

2.1. ZigBee network

ZigBee has recently been used in the field of mine safety for a range of applications mostly in underground coal mines as an automatic meter reading system, security system and remote control alongside supporting other WSNs [17,18]. The reliability and security of the ZigBee network performance have nevertheless been extensively considered. The ZigBee network applications in underground mines are limited considering the narrow bandwidth of up to 250 kbps (kilobits per second) at a frequency of 2.4 GHz [19]. To support the performance of these applications, ZigBee networks profit from IEEE 802.15.4 protocol [20]. IEEE 802.15.4 characterises the physical and medium access control layers of wireless personal area networks. The physical layer is the hardware for the network communication and enables operation in different frequency ranges. The medium access control layer is responsible in providing reliable data transmission and communications between a node and its immediate neighbours. It also avoids data collisions and improves network efficiency [21].

The reliability of ZigBee network under outdoor condition was verified by our team research, but the narrow space of underground environments has significantly intensified the signal strength to transmit data between two fixed nodes for a specified distance [15,22]. A recent study by authors has confirmed a similar conclusion and showed a stable communication of packet deliveries between fixed ZigBee nodes for the underground monitoring and communication system in different openings [9]. Consequently, ZigBee applications considering developed ZigBee nodes by our group research for underground monitoring and communication in the field of safety and health are investigated in real cases. Based on the experiments, to utilise underground ZigBee applications of sensing the environment and texting messages, scheduling specific times for data transmission through the network are required. In other words, measuring and sending data by sensor nodes are set in different time intervals to avoid any network congestion and to improve network performance.

2.2. Geographic information system

GIS is based on computer programs used for storage, modelling, retrieval, mapping and analysis of geographic data. In this system, spatial features of a specified environment are stored and manipulated in a coordinate system, which refers to a specific place. GIS

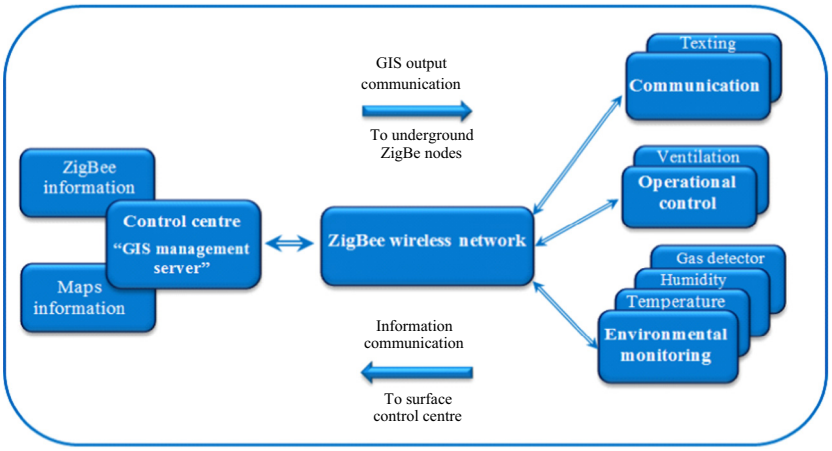

Fig. 1. Architecture of monitoring and communication system in underground mines.