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Safety barrier warning system for underground construction sites using Internet-of-Things technologies

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ABSTRACT

This paper proposes an Internet-of-Things-based (IoT-based) safety barrier warning system to achieve a safer underground construction site. A focus of this paper is to establish a hazard energy monitoring system and use IoT to generate early warnings and alarms as dynamical safety barriers for hazard energy on underground construction sites. To ensure the performance of the proposed system, the hazard energies and their coupling mechanisms was analyzed to provide safety barrier strategies and scenarios for avoiding unsafe behaviors and unsafe status of construction equipment and workers' environment. The IoT technologies, such as meter-level of RFID-based location and tracking technology, centimeter-level of ultrasonic detection technology, and infrared access technology and so on, were developed in three-tier network architecture to help workers change their risky behaviors and avoid accidents on the changing construction site. The implementation in Yangtze River-crossing Metro Tunnel Construction site has shown the safety performance was improved and the occurrence of accident caused by hazard energy on site could be prevented.

1. Introduction

Numerous underground metro construction projects in China result from rapid progress of urbanization of the country. Based on data from Ministry of Housing and Urban-Rural Development of the People's Republic of China, there will be 36 cities with a total of 3004 km of metro lines under construction, including 2047 stations [1], causing rapid development of related industries and increasing employment opportunities, alleviating the increasing pressure on urban public transport, and improving the image of China's metropolitan areas. However, underground metro construction accidents happen frequently owing to unpredictable geological and hydrological conditions, poor monitoring of unsafe behavior, and unsafe condition of construction equipments and work environment [2]. For example, on May 6, 2013, a tunnel shaft of Xi'an metro line 3 collapsed during tunnel excavation. The accident resulted in 5 fatalities, with the youngest being 22 years of age. The main reason was the unawareness of breaking into a dangerous zone in the tunnel during excavation, combined with excessive excavation of the tunnel face and poor geological conditions. Research had shown that about 80–90% of accidents are associated with workers' unsafe behavior or unsafe condition of construction equipment and work environment, especially in underground construction industry [3,4]. Therefore, there is a need to raise awareness of workers of the potential hazard on site dynamically and automatically.

For a long time, there has been considerable interest in the modelling and analysis of safety features and accident prevention. The Energy Based Analysis (EBA) approach is a general safety analysis technique based on the famous ‘hazard-barrier-target’ model [5]. Exposure to the agent ‘hazard energy’ is the starting point in the case of any damage or accident. To prevent an accident, the hazard energy build-up and coupling must be prevented by erecting a barrier between them [6]. Interest has been especially great in the off-shore, chemical, and nuclear industries, and accordingly research has been heavily oriented toward major hazard energy [7]. However, this type of industry and these safety barrier applications represent only the facility operation field of accident prevention. Construction workplaces, and to an even underground construction site, produce many more injuries and fatalities than in operation phrase. Despite this, the monitoring of hazard energy and safety barrier analysis has received less attention in construction industry. There are many research challenges in this area with complex technical and organizational settings, with changing environment and workers, which require sophisticated methods and techniques to further improve preventive measures.

Utilizing the system of rewards and penalties, safety training, construction standardization, and other tools may assist in improving safety performance of construction industry. However, they require

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additional enhancement for better outcomes. Internet of Things (IoT) technology has been applied in a wide array of applications to provide solutions to manufacturing and transportation [8]. For instance, a reformed safety behavior modification approach by integrating a location-based technology with BBS was proposed and tested in a construction site in Hong Kong, followed by details of the corresponding on-line supporting system, Real Time Location System (RTLS) and Virtual Construction System (VCS) [9]. Similarly, a stochastic state sequence model to predict discrete safety states was proposed through a Real-Time Location System (RTLS) on construction sites, which aimed at identify the hazardous level of a project or individual person over a period of time [10]. In terms of safety management, the identification of accident precursors, training and inspection are three main aspects involved in improving safety behavior with IoT technologies. These considerations have formed an interest to combine hazard energy monitoring and safety barrier management as well as IoT in a consistent framework, which needs to be multidisciplinary. Its principal aims are to present a method that applies the functions of monitoring hazard energy dynamically and sending warnings as safety barriers automatically to demonstrate how it works in practical accident prevention in construction.

This paper describes a new safety barrier early warning system for hazard energy on construction site using IoT technologies. The goal of the presented research was to verify the efficiency and reliability of the system for monitoring and setting safety barriers with the use of early warnings for different types of hazard energy. The following presents details of the background, theory framework, system design, and case study. Section 2 presents a review of related theories and techniques (such as concept of hazard energy and safety barrier, IT-based construction safety management and so on) in this study area. Section 3 illustrates the IoT-based hazard energy monitoring framework, including hazard energy identification process, monitoring data requirements and collection and early warning mechanism. Section 4 introduces the design and development of the IoT-based safety barrier warning system. Section 5 is a case study of the system on the Yangtze River-crossing metro tunnel construction site in Wuhan, China. Finally, Section 6 presents conclusions and proposals for further research.

2. Hazard energy and safety barrier in construction

2.1. Concept of hazard energy and safety barrier

An accident was defined as an unscheduled, unexplained random effect in several decades before [11]. Among many accident causation theories, EBA model was originally based on the successive works of Hienrich's domino theory back in the 1930s, Haddon in 1966 and Gibson in 1961 [6]. EBA models an accident as a contact between a hazardous agent (HA) and a target (a vulnerable and valuable object), by transferring from one domino to another [12]. The target notion is used generally, for people, the environment or physical assets and so on. The HA may be any danger source, usually expressed as “hazard energy”, which can damage a target [13]. For example, an abnormal exchange of energy exceeding the body's resistance was seen as the cause of accidents and the basis for an injury.

A barrier can be defined as a physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents [14]. In the simplest way, safety barrier is a protector of a target from an HA impact. Using this definition, knowledge and information, and the distance warning between energy and target are also considered as safety barriers [15]. A safety barrier system is a system that has been designed and implemented to perform one or more barrier functions, such as a pressure protection system [15,16]. A safety barrier system will sometimes have several safety barrier elements that perform one or more barrier subfunctions. Safety barrier systems can also be characterized by their nature, such as technical, operational, and organizational [16]. Technical systems can in turn be divided into safety

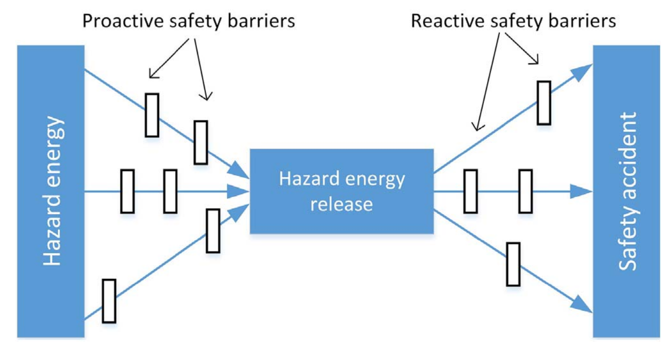

Fig. 1. Proactive and reactive barrier functions in the hazard energy releasing prevention.

monitoring systems, safety warning systems and automatic risk reduction facilities [17]. Operational barrier systems are tasks performed by a manager, or team of managers, such as to manually operate open a valve or a door [18]. Organizational barrier systems are personnel responsible for, and directly involved in, realizing one or more barrier functions [19].

Studying the relationship between energy-barrier-target reveals a rich set of hazard control alternatives, spanning from inherent safety, through control of energy release, to mitigation contact between energy and target, and recovery enforcement [20], as shown in Fig. 1. A series of hierarchically organized protective layers were proposed to assess the accident scenarios systematically [5]. These protection layers can be reactive (e.g. personal protected equipment) or proactive (e.g. a warning system) [12]. Reactive barriers implement the safety function by the mere presence of their elements, while proactive barriers perform an action in response to a certain state or condition always including a sequence of detection-diagnosis-action [6]. Safety barrier and hazard energy releasing prevention diagrams have become popular methods in risk analysis and safety management [15]. Developing the specific diagrams for investigate the hazard energy and target behaviors, separately, and using the safety barrier nodes in these diagrams, to support quantitative risk analysis, distinguishes this approach from the previous works [17].The advantage of above hazard-energy-based model and safety barrier system is that they are structured ways to consider the events related to a safety system failure, and helps to identify the system's weak points, which have an insufficient level of risk control [21]. To prevent an accident, the hazard energy build-up and their coupling must be prevented by removing one of the intermediate dominoes or by erecting a safety barrier between them [13,22].

2.2. Hazard energy coupling in construction

As mentioned above, different types of hazard energies exist at the same time during the construction process. Distinctions were made between radiation, mechanical, thermal, chemical and electrical energy leading to different types of injury and potential damages [22]. Most of them exist simultaneously in underground construction projects, as shown in Fig. 2. Actually, an abnormal exchange and combine of different types of hazard energies play an important role in an accident, which could induce the energy build-up in the system exceeding the system resistance. The underground excavating process is nonlinear with multiple hazard energies coupling and is influenced by many random and uncertain factors. Consequently, it is very difficult to obtain a comprehensive and accurate hazard energy coupling model of the whole underground construction by depending only on the theoretical analysis method. However, investigation of uncontrolled energy coupling as a direct cause of injury is the foremost step in injury analysis [23].

For construction project, the different patterns or mechanisms of hazard energy coupling, i.e., the complex interaction between several different hazard energies, are determined by the composite structure