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Building information modeling in combination with real time location systems and sensors for safety performance enhancement

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ABSTRACT

The misuse (including nonuse) of personal protective equipment (PPE) directly catalyzes the changes from incidents to critical accidents and diseases. However, to date, the main control over PPE use is through manual visual inspections, which is time-consuming and more often than not biased. Moreover, the current applications of technologies such as RFID have not guaranteed the proper use of PPE on site.

This study introduces a novel approach towards automated remote monitoring and assessing how the PPEs are worn through integrating pressure sensors and positioning technologies. In order to realize such automated control, potential technologies are reviewed and a wireless network architecture composed of end nodes, repeaters/checkpoints and coordinators is considered. The real time location system (RTLS) and virtual construction are developed for worker's location tracking to decide whether the worker should wear helmet and give a warning, while the silicone single-point button is designed to show whether the PPE is used properly for further behavior assessment. The process of data synchronization and fusion of location coordinates and pressure data is described in detail and the system is tested in an open area experiment to prove its feasibility.

1. Introduction

Construction has been always notorious as one of the most dangerous industries due to its unique nature (Jannadi and Bu-Khamsin, 2002), such as outdoor operations, work-at heights, complicated on-site plants and equipment operation coupled with workers attitudes and behaviors towards safety (Choudhry and Fang, 2008). In Hong Kong, construction industry is one of pillar industries as it employs millions of site workers. But this industry has experienced a shortage of labors these years and companies have to reach hands to people elder or with little relevant working experience. In this situation, how to ensure the safety and health of workforces is becoming a more challenging and complex task. The misuse of personal protective equipment (PPE) like safety helmet and respirator contributes directly to the severity of accidents and is closely connected with many occupational diseases like head injuries, hearing loss, dermatological disease and pneumoconiosis. As a result, it is recognized as one of the twenty non-negotiable unsafe behaviors on work site.

To reduce the misuse behaviors and improve safety performance, the current ways have mainly emphasized three aspects: (1) improving PPEs in technological aspects; (2) enhancing on-site safety management procedures and protective measures; and (3) providing more PPE use trainings. These technical and organizational actions are useful but have reached a world class bottleneck: although expenditures in safety management manpower, protective measures and safety trainings have been increasing annually, the accident rate has decreased little after the implementation of compulsory construction industry safety training certificate (education) and Pay for Safety Scheme (punishment). Their ineffectiveness is attributed to: (1) they rely on well trained and highly experienced safety observers, (2) subjective observations or surveys are needed that result in omissions or biases, (3) they do not allow PPE traceability or real-time monitoring for in-time feedback and (4) outcome-based group level assessment conceals personal performance unduly.

One of the solutions to this problem are positioning and sensor technologies because they have the potential to foster better safety and productivity by tracking construction resources (labor, equipment, materials, etc.) anywhere and anytime (Cheng et al., 2011; Ergen et al., 2007; Torrent and Caldas, 2009). Many related technologies like RFID and cyber physical system have been employed for PPEs use monitoring, but these methods can only detect whether the workers carry the PPEs with them without any judgment on whether they use the PPEs correctly in the place needed. Therefore, the goal of this study is to investigate the better prospect of automatically identifying and

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assessing PPE misuse behavior on personal level, and providing feedback sufficiently and quickly to modify the unsafe behavior. In doing this, the idea is developed in the context of helmet misuse on a worksite. The supporting system has the primary functions of tracking workers and danger sources, sending our warning signals and assessing helmet misuse behavior. The warnings and worker responses are recorded for use in analyzing individual safety performance and providing timely feedback.

The paper is organized as follows. First a detailed background is provided, describing PPEs use problems on site, the existing methods for behavior improvement and insufficiencies. Then potential technologies for location tracking and sensor are provided. A conceptual method of positioning and sensor technologies-enhanced PPE use management is then developed, followed by details of the supporting system. The application of the system is then demonstrated and verified on a live construction site in Hong Kong. Final comments are provided concerning further research work needed and prospects for extension to other situations involving safety considerations.

2. Background

2.1. Current PPE misuse and management on site

According to Occupational Safety and Health Council (OSHC), PPE means any protective equipment that protects users from being exposed to a potentially hazardous environment. PPE can be divided by the protection parts or functions of human body such as head protection, hand protection, body protection and respiratory protection. Some famous PPE are safety helmets, safety shoes, safety belts or ear muffs. PPE is highly effective to avoid injury if wore and fitted properly when workers come into contact with a potentially hazardous situation (Dingus et al., 1993; Long et al., 2013) such as toxic chemicals, electric shock, slippery floor or falling objects. Lack of PPE use is repeatedly noted as a contributor to occupational injuries (Contreras and Buchanan, 2012). For example, hard hats are designed to protect against concussions and traumatic brain injuries caused by strikes to the head. The nature of construction calls for proper use of hard hat on the job. In the United States, the construction industry has the highest number of workplace head injuries due to the improper/use non-use of hard hats. Beyond safety problems confusing construction for decades, some occupational chronic diseases, such as hearing loss, dermatological disease and pneumoconiosis, caused by misuse of PPEs in bad environment ruin the quality of life in long run. Meanwhile, the common phrase “dress for success” applies beyond white-collar workers, which means clear positive connections have been found between satisfaction of PPE and work clothing, self-efficacy, and overall satisfaction of trades work (Wagner et al., 2013).

PPE misuse is often neglected because current assessment is mainly focused on visible outcomes such as critical injuries and accidents, and it is hard to identify hazardous behaviors in time (SWA, 2013). Undoubtedly, using PPE is a factor which would be positively correlated to safety performance on construction sites and became one of the most important factors affecting safety performance (Sawacha et al., 1999). PPE misuse records are mainly kept by self-reporting, which is inhibited by a blame culture for error, time-consuming paperwork, and lack of feedback on how the information reported has been used (Van Der Schaaf and Kanse, 2004). To solve these problems, current activities mainly involve modifying PPE use behavior through safety regulations and training (Kaskutas et al., 2013), and improving safety attitude through better organizational safety culture (Fung et al., 2012). These methods are useful but do have disadvantageous such as:

(1) being unable to remedy the limitations of human vision and ability to detect all surrounding danger sources;
(2) largely relying on wandering inspection and lagged (outcome) measurement, which fails to provide feedback to change unsafe behaviors in time. The main reasons resulting in failed protection are located in: disability of PPEs to fulfill a nominal safety function (Mäkinen and Mustonen, 2003), or unexpected behaviors in hazardous situation (Choudhry and Fang, 2008). As summarized in Fig. 1, the PPE-oriented researches are devoted to technical improvement for better protective and reminding function.

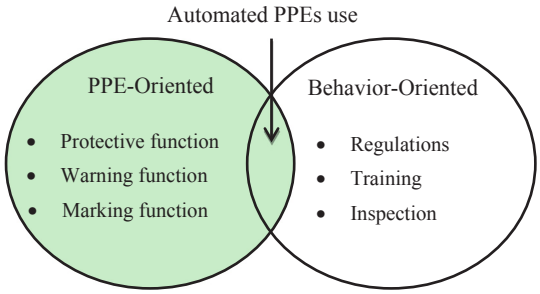

Fig. 1. The current methods to improve PPE use.

Many international safety and health organizations like OSHA (2003) made a detailed and comprehensive list of protective functions for multiple PPEs in construction. For example, the filter lenses for protection against radiant energy should be selected and examined in terms of plate thickness and minimum protective shade according to different electrode size and arc current. What’s more, Mäkinen and Mustonen (2003) analyzed 25 electric arc accidents that occurred in Finland in 1996–1999 to find out the different technical requirements of protective clothing. And there are 12 factors that affect the acceptability of head protection at work including weather protection, thermal properties, tactile properties, absorptivity/permeability and mass distribution et al. (Hsu et al., 2000). To fulfill these requirements, many methods are implemented, such as helmet made by composite materials with thermoplastic matrices and a reinforcement of natural fibers (Murali and Nagarani, 2013). Except for the detailed technical improvement to ensure better protective function, many other factors like the way of warning and marking also play very important roles in promoting PPE use. As proven by Dingus et al. (1993), a warning which contains information pertaining to the specific consequences of using the product, and a warning situated in such a way that the consumer must interact with the label (increasing label noticeability) can improve safety performance effectively.

With regard to another reason leading to protection failure, the misuse of PPEs is identified as a serious and unforgivable unsafe behavior on worksite. According to the decision making process, the factors influencing use of PPE and consists of three primary branches: perceptions of hazards and risks, “barriers” to PPE use, and enforcement and reinforcement (Lombardi et al., 2009). Many regulations are established to minimize the cost of compliance like the contractors are responsible to provide qualified PPEs for workers. To improve the safety perception and changing attitude, training is always the popular way both in academy and practice (Mäkinen and Mustonen, 2003). During the implementation phase, the behaviors are inspected and assessed for feedback to correct the unsafe behavior finally. To realize efficient behavior inspection, many technologies like Mobile passive Radio Frequency Identification (RFID) was applied to perform automatic site access, time recording, and completeness control (Kelm et al., 2013). And there was cyber physical system set up for real-time PPEs monitoring by keeping the PPEs in close range (Barro-Torres et al., 2012). But we identify three weaknesses of these similar methods and technologies: (1) these methods cannot ensure the proper use of PPEs, (2) do not take conditions into consideration automatically where different kinds of PPEs are needed, and (3), the wearable devices applied are relatively heavy and difficult to apply in real construction sites.