Automation in Construction 36 (2013) 38–52

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Mobile passive Radio Frequency Identification (RFID) portal for automated and rapid control of Personal Protective Equipment (PPE) on construction sites

Agnes Kelm [a,1], Lars Laußat [a,2], Anica Meins-Becker [a,3], Daniel Platz [a,4], Mohammad J. Khazaee [a,5], Aaron M. Costin [b,6], Manfred Helmus [a,7], Jochen Teizer [b,*]

[a] Bergische University of Wuppertal, Civil Engineering Faculty, Chair of Construction Management & Economics, Pauluskirchstr, 7, 42285 Wuppertal, Germany
[b] School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Dr. N.W., Atlanta, GA 30332-0355, USA

ARTICLE INFO

Article history:
Accepted 20 August 2013
Available online 14 September 2013

Keywords:
Secure access
Compliance checking
Gates and portals
Human behavior
Lagging and leading indicator safety data
Personal Protective Equipment (PPE)
Radio Frequency Identification (RFID)
Safety and health
Construction workforce morale
Worker education and training

ABSTRACT

Although personnel entering a construction site are mandated to wear Personal Protective Equipment (PPE), hardly ever is PPE checked for accurateness, completeness, or whether its shelf-life has expired. Various commercially-existing automated identification (ID) and information technologies (IT) were used to design a mobile Radio Frequency Identification (RFID) portal for checking the PPE compliance of personnel. When such gates are positioned at the entrance or within construction sites and once low-cost passive RFID tags are embedded or attached to PPE, automatic site access, time recording, and completeness control can be performed. These improve the logistics of the existing compliance checking process and provide users with timely feedback. Results to "personnel entering a construction site" demonstrate how the safety process, especially the awareness among personnel wearing PPE, can be pro-actively managed and controlled. Data further suggests the limitations of the developed approach and its potential for gathering leading safety indicator data.

Published by Elsevier B.V.

1. Introduction

Work-related accidents, illegal employment, undeclared jobs, and failure to comply with minimum wages are problems which occur on many construction sites around the world. They often lead to negative headlines in public media, personal loss or injury, and other economic losses such as collateral damage [1,2]. In addition, the widespread theft of construction equipment, tools, and materials is another known problem in the construction sector [3]. Using unauthorized or unqualified personnel also causes poor quality of construction work and adds to the life cycle project cost in the long term [4–6].

To solve this problem, both employers and employees should take pro-active actions. Various commercial applications exist which are using barcodes and RFID for material tracking, inventory control, manufacturing process and control, and productivity accountability. RFID technology employs smart chips or tags that are either embedded or attached to objects that can then be identified. Using RFID antennas, gates, or readers they can also be tracked. Besides such hardware that reads and writes information to the RFID tags, the tags are "active", "semi-passive", or "passive". "Active" means the tag requires an internal battery supply to transmit radio signals and ID. A "passive" tag requires no battery power and operates only by interrogation of an external antenna. A passive tag generates an electromagnetic pulse that transmits the ID stored on its chip. The information can then be linked in real-time to a database and used for further processing in applications domains describe above.

In construction, RFID deployment has focused mostly on material tracking with active RFID [7–9] and was combined with other sensing technology for rapid locating purposes [8,9]. These approaches predominantly gathered information related to valuable construction parts. There are a number of these applications where RFID has been used for logistics, but presently little attention has focused on

* Corresponding author. Tel.: +1 404 894 8269; fax: +1 404 894 2278.
E-mail addresses: agnes.kelm@uni-wuppertal.de (A. Kelm), laussat@uni-wuppertal.de (L. Laußat), a.meins-becker@uni-wuppertal.de (A. Meins-Becker), d.platz@uni-wuppertal.de (D. Platz), khazaee@uni-wuppertal.de (M.J. Khazaee), aaron.costin@gatech.edu (A.M. Costin), helmus@uni-wuppertal.de (M. Helmus), teizer@gatech.edu (J. Teizer).
http://www.baubetrieb.de (M. Helmus), http://www.rapids.gatech.edu (J. Teizer).
[1] Tel.: +49 202 439 4109; fax: +49 202 439 4378.
[2] Tel.: +49 4371 8979 241; fax: +49 202 439 4378.
[3] Tel.: +49 202 439 4109; fax: +49 202 439 4314.
[4] Tel./fax: +49 202 439 4378.
[5] Tel.: +49 202 439 4109; fax: +49 202 439 4415.
[6] Tel.: +1 404 423 1161; fax: +1 404 894 2278.
[7] Tel.: +49 202 439 4114; fax: +49 202 439 4314.

0926-5805/$ – see front matter. Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.autcon.2013.08.009

applying an automated process or system for ensuring that construction personnel wear their required PPE and also adhere to safety precautions regarding PPE [10]. As construction sites provide many harsh work environments, for example, confined spaces and dust controlled areas, it is generally up to the individual or supervisor, to check that appropriate PPE is worn at all times. Although the "buddy-principle" is applied in construction where every worker should be concerned about their own and their colleague's health and safety, PPE inspections occur infrequently, are opinion-based, and thus can be error-prone [11].

Several work environments, including construction, require the workforce to wear PPE. PPE includes but is not limited to clothing, hardhats, shoes, eyewear, masks, and other assisted breathing devices. Examples are safety vests, gloves, steel-toed shoes, ear-plugs, etc. Each work environment has its own PPE requirements that must be worn according to rules and regulations by an individual prior to performing a work task. For example, workers on a building construction site may be well protected wearing a hardhat, safety vest, goggles, gloves, steel-toed shoes (in addition to wearing long pants and a long-sleeved shirt). Other work environments such as work in power plants may require more stringent and specialized design and use of PPE. Several standards exist that determine which PPE is appropriate and safe to use. Each PPE has a shelf-life and expiration date. Many hardhats, for example, have an expiration date printed on the inside of the helmet. Any PPE, however, is hardly inspected for proper quality or completeness.

As employers are required to provide a safe work environment for their employees (may vary by country) [12] and it is within the self-interest of the employees to work safely, the least PPE that needs to be maintained on construction sites follow the legal requirements. Often employers apply more stringent methodologies which go far beyond the use of PPE. These are then called best practices. However, many employers often but only manually document their actions and processes accordingly.

In sum, a need exists for a system that applies modern data gathering and control principles that comply at least with occupational health and safety regulations. The following reviews inventions and existing research found in the literature. The research methodology and scope are presented. The developed system consisting of passive RFID, data processing, and management technology is then explained. A field application is illustrated afterwards. Additional benefits and current limitations such as the automatic recording of working hours will also be discussed.

2. Background review

2.1. Importance of PPE for worker's health and safety

Although criticized, [13] has focused on management's responsibility for accidents. Employers are generally required by law to provide a save work environment [11]. It is their responsibility to provide a hazard free work environment. When needed, actions in design and planning phase must be taken to establish control mechanisms such as engineering improvements, best work practices, and administrative initiatives. Workers, however, remain the basic cause of accidents in behavior models. Since people make errors under various situations and environmental conditions, most of the blame in accidents usually falls on workers. Large efforts have been taken to categorize and define human error and risk prevention techniques [14–18], but as the most related publications state, the lowest possible level of possible control in safety is workers wearing appropriate PPE.

PPE is potentially the last barrier according to [17] and might as well be the final option to alleviate the effects of a possible accident. Despite accident causation and prevention techniques, motivating and controlling workers to wear PPE needs its own efforts. Employers may address the use of PPE in three ways: (1) education and training, (2) incentives, and (3) enforcement. A case study by [19] has shown that workers may not wear PPE because they either forget or find it uncomfortable to wear PPE. Other factors were found by [20]: (a) PPE may impact productivity, (b) exposure to a hazard is short and thus PPE is not needed, and (c) inadequate or not available education and training for using PPE. A recent study by [21] further identified two additional factors that affect workers in their decision of not using PPE: (a) limited perception of hazards and risks in the work environment and (b) no enforcement nor reinforcement. To solve these issues, employers can improve the consistency of PPE use by applying best practices assisted through novel technology. These could then meet the employer's responsibility of enforcing safety rules by undertaking changes in controlling PPE and related processes.

On the other hand, [22] concluded that a good safety climate influences the workers' risk behaviors positively. They found that the level of ambivalence toward wearing PPE is influenced by the safety climate including, but not limited to: (a) the company's overall safety strategy, (b) the involvement of senior management, and (c) the attitude of supervisors towards safety. A case study by [23] investigated 621 accident reports of work related fatal falls in Taiwan and realized the improper use of PPE and use of broken PPE as contributing factors to occupational fatal falls. The report concluded that enforcing the use of fall protection systems and inspecting the protection systems and tools could have been of crucial importance to mitigate most of the recorded accidents.

Another study by [24] found that inappropriate use or not using PPE made United Kingdom's construction the least safe industry sector in the UK while having the most work related fatal injuries. The primary reasons were stated "no PPE recognized", followed by "PPE not used". It was further concluded that poor site supervision was the key deficiency when PPE was not used. The study further investigated the investment and loss associated to safety. Although the industry invested an overall (estimate) £252 m in 2001/02 in PPE, additional £157 m in costs that related to the mitigation of accidents could have been saved if employers had invested initially in PPE.

In sum, employers (owners and construction companies) can potentially improve the rate workers wear PPE on construction sites by putting more value on safety education, training, and enforcement. One way is a system that might not be too intrusive, but reminds workers on a daily basis or at the beginning of hazardous work that appropriate PPE must be worn at all times. This could be emphasized by erecting a PPE control gate at the entry of or close to hazardous work spaces at or within construction sites.

2.2. Problems in PPE inspection, construction site access, time recordings, and ID systems

One task of logistics at construction sites is to perform access control of personnel. On large construction sites, several hundred or more workers are generally employed and on site, simultaneously. There are also many subcontractors, vendors, visitors, etc. who may happen to enter the construction site on a daily basis. It is common sense that unauthorized persons should be denied entry to the site for: (a) safety reasons, (b) theft prevention, and (c) illegal employment. To ensure all of these, construction sites are protected typically by a fence. Depending on the size of the construction site, the owner or construction company may hire additional access control, for example gatekeepers and/or security services, that coordinate entry/exit to/from the site and in addition patrol the site's interior and boundaries. The following modern means are available to identify and grant a person permission to access a construction site:

- *Identification (ID) cards for personnel:* Identity cards are issued to control personnel from entering/exiting a construction site. Most ID cards have the size of a credit card, carry name and potentially