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FPSWizard: A web-based CBR-RBR system for supporting the design of active fall protection systems

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ABSTRACT

Fall from height is a perennial problem in the construction industry. Active fall protection system (AFPS) is frequently a must in situations where working conditions are difficult and other controls are not feasible or inadequate. However, the design and selection of AFPS are still problematic in the construction industry. This paper aims to develop an online knowledge-based system, *FPSWizard*, to support the design and selection of AFPS. The hybrid system adopts a combination of case-based reasoning (CBR) and rule-based reasoning (RBR) to improve retrieval performance. *FPSWizard* is meant to recommend suitable AFPS based on similar past design cases. Potential end users, such as professional engineers and safety professionals, can use the system as a decision support system when they are selecting and designing a solution to the work-at-height problem at hand. A total of fifty stored cases were created based on actual work scenarios and AFPS designs in the construction industry. A case structure was also created using the AFPS-Ontology. The system was assessed using a leave-one-out cross validation approach, where fifty cases in the case base were used to test the retrieval performance of the system. The hybrid CBR-RBR approach had an average positive predictive value (PPV) (or precision) of 90%. In comparison, a pure CBR approach had an average PPV of 76%. *FPSWizard* forms an important part of an intelligent system which provides comprehensive solutions to fall from height. This paper also made important strides towards intelligent safety engineering and management in the construction industry.

1. Introduction

Construction workers are at risk of falling from height across the lifecycle of a building, from construction to maintenance, renovation, and demolition [1]. Working at height is dangerous in nature. Falls from height are high risk occupational accidents in many countries, such as the U.S. [2], the U.K. [3], Australia [4], Singapore, and New Zealand [5]. For example, falls accounted for 35% of all workplace fatalities and 43% of major injuries in Singapore in 2015 and construction remains the top contributor of fall-related injuries [6]. These injuries caused huge suffering, loss, and economic costs. The Occupational Safety and Health Administration (OSHA) estimated that each fall result in claims between US$50,000 and US$106,000 [7], and this amount does not include indirect or intangible costs like work stoppages, morale issues, societal and personal costs.

In practice, preventing fall from height has always been one of priorities of site safety management. Fall hazards are identified and communicated to workers through job safety analysis, task analysis, or safe work method statement. In order to protect workers working at height, control measures must be comprehensive and multifaceted. A combination of control measures is usually adopted, including elimination (e.g., prefabricating wall frames horizontally before standing them up), substitution (e.g., using mobile elevated work platform instead of ladders), engineering controls (e.g., guardrails), and administrative controls (e.g., work-at-height rules and procedures). Fall protection systems can be classified into two categories: passive and active fall protection systems. Passive fall protection system is “a means of providing fall protection that does not require workers to wear or otherwise use fall-protection equipment or to have any special knowledge or skills related to this system.” [8]. PFPS does not require any use of personal protective equipment (PPE) or active participation of workers. Typical examples include guardrail systems and safety nets. By contrast, active fall protection system (AFPS) is defined as “a means of providing fall protection that requires workers to take specific actions, including wearing (and otherwise using) personal fall-protection equipment and following prescribed procedures.” [8]. Common AFPS includes travel restraint and fall-arrest systems. A travel restraint system is used to prevent its users from reaching unprotected edge or

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opening, while a fall arrest system is an assembly of components (e.g., full body harness, connectors, lanyard, energy absorber, and anchor) that will arrest a worker's fall. Fall arrest systems generally include horizontal lifeline systems (HLL) and vertical lifeline systems (VLL).

PPE is the least effective control measure in the hazard control hierarchy and often considered as a last resort. However, it is frequently a must in situations where working conditions are difficult and other controls are not applicable or inadequate. For example, installing a safety netting system may not be an applicable solution for old roof maintenance and repairing. When PFPS solutions and other controls are not applicable and inadequate, AFPS is the next best solution. In general, there are two problems with the use of AFPS: workers' misuse/non-use of AFPS and inappropriate design/selection of AFPS. The first problem is often explained and managed by investigating the effects of organizational, group, and human factors on workers' safety knowledge, motivation, and behavior [9,10]. By contrast, the second problem has received less attention. The design and selection of AFPS is a knowledge and experience intensive process [11]. It is highly dependent upon dynamic construction environments, tasks, location, and workers. It may be difficult for designers to select an appropriate type of AFPS because they work upstream of a construction project and thus face great risk of failing to anticipate job tasks, workers, and involved building elements. This is even more challenging for novice engineers who may not have adequate knowledge and competency to select and design a reliable solution to a given working at height problem. For example, AFPSs were often poorly designed by users (e.g., contractors) without proper endorsement from professional engineers (PEs) [12]. Even PEs often adopted wrong calculation methods with invalid assumption when they design AFPS [13]. PEs may underestimate the maximum arrest force exerted on a worker when a fall arrest system stops a fall. Another common mistake is that inadequate “minimum clearance below the platform” is specified based on incorrect calculation approach. Consequences of these mistakes are that a worker who is arrested by the fall arrest system can be injured, or even killed, by the arrest force or an obstacle or the ground before the fall arrest system stops the fall. In practice, PEs must be knowledgeable in a wide range of fall protection systems and different ways to combine the equipment and systems in varying environmental and site conditions. However, human judgement is always subject to serious fallacies. Relying only on intuition and experience may lead to inappropriate AFPS designs and can cause serious consequences.

Considering the lack of competency in designing and selecting AFPS in the construction industry [12], a knowledge-based system can assist both PEs and contractors with decision making under uncertainty. With the advancement of artificial intelligence (AI), a number of established AI techniques such as case-based reasoning (CBR) and rule-based reasoning (RBR) can be used to provide reliable recommendations. Such a system can relieve cognitive burden of designers and save time. However, to the best of the authors' knowledge, there is rather limited application of these AI techniques to the design of AFPS. In order to fill the research gap and promote the use of AI in construction safety engineering and management, this paper aims to develop an online knowledge-based system, *FPSWizard*, to support the design of AFPS using a combination of CBR and RBR. *FPSWizard* is designed as a web-based decision support system which has the ability to identify solutions, i.e., the type of AFPS, to new work-at-height problems based on similar past design cases. Potential end users, including professional engineers, contractors and safety professionals, can use the system as an online assistant when they attempt to identify a solution to a work-at-height problem at hand.

2. Background

2.1. Fall from height in the construction industry

Fall from height has received significant attention from scholars. Early attention was mainly on identifying root causes and contributing factors of fall accidents. For example, Chi [14] developed a coding system to categorize fatal falls in terms of fall causes, fall location, individual factors, and company size. The coding system can be utilized to identify important contributing factors and control measures. Huang and Hinze [15] investigated the root causes of fall accidents based on the data from OSHA. A number of contributing factors were identified, including lack of safety training and human error. Similarly, Chan [16] identified 12 common contributing factors by analyzing 22 fatal industrial fall accidents in Hong Kong. Based on the findings, they proposed five strategies to reduce fall accidents, including (1) provide and maintain a safe system of work, (2) provide a suitable working platform, (3) provide safety information, training, instruction, and supervision, (4) provide suitable fall arresting system/anchorage, and (5) maintain safe workplace. On the other hand, Wong [17] adopted the Human Factor Analysis Classification System (HFACS) to identify and classify the root causes of fatal fall accidents. Within the area of human factors, Goh and Binte Sa'adon [10] adopted the theory of planned behavior to model the cognitive factors influencing the unsafe behavior of scaffolders.

Risk identification and assessment are important processes to control falls. In order to facilitate the process, Sa [18] compared the risk factors of falls between commercial and residential roofers. Results suggested that residential roofers are more likely to fall than commercial ones. Aneziris [19] developed sixty-four logical models to quantify fall risk. In addition, Nguyen [20] proposed a Bayesian network (BN) based approach to diagnose the accident risk of working at heights.

Information technologies have been used to help reduce fall accidents and injuries. For example, Navon and Kolton [21] developed an automated model that can identify dangerous work-at-height activities and areas. The schedule is integrated into the model which enables it to produce both textual and graphical reports that correspond to the schedule. The automated model was implemented in a prototype written in Visual Basic (VB), AutoCAD, and MS Project. More recently, Qi [22] developed a PTD (prevention through design) software tool to help designers implement best practices to prevent fall accidents. Using the PTD tool, automatic safety checking can be performed by using BIM technology and a knowledge base that was designed based on best practices. These efforts were aimed at reducing fall accidents by improving building design and optimizing production planning. Supported by these advancements, a part of fall hazards could be either eliminated, substituted, or managed by engineering and administrative controls. However, personal protection equipment, including AFPS, is still required as a last line of defense to protect workers in many situations [12]. Despite the importance, no research, to the best of the authors' knowledge, has been conducted using information technologies to support the design and selection of AFPS.

2.2. Design of AFPS

In order to support and facilitate the design of AFPS, standards were developed at the national level, such as ANSI/ASSE Z359.6:2009 by American National Standards Institute, American Society for Safety Engineers [23], Z259.16-15 by Canadian Standards Association [8], and SS607: 2015 by Singapore Standards Council [24]. These standards specify requirements for the design and performance of complete active fall-protection systems. Despite these standards and specifications, the design and selection of AFPS are still problematic in the construction industry. For example, Goh and Wang [12] pointed out that many AFPS are designed by PEs on an ad hoc basis and assembled by contractors who purchase the individual components. They evaluated eleven cases of HLL system design and concluded that all cases were inadequate and that many PEs were not familiar with these design standards. The lack of knowledge was reflected by the fact that PEs used wrong assumptions and calculation methods. For example, PEs tend to focus on static force rather than dynamic force on lifeline and users when a fall occurs [13].

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