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Ontology for design of active fall protection systems

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ABSTRACT

This paper aims to develop an ontology (AFPS-Onto) which formalizes the knowledge of active fall protection system (AFPS) design, with attempt to facilitate knowledge sharing and reuse. METHONTOLOGY was adopted as a method to build the AFPS-Onto. The AFPS-Onto consists of nine core concepts: hazard, actor, task, ifc building element, construction method, constraint, safety resource, hazard control measure, and residual risk. The concepts, relations, attributes, and axioms were coded using Protégé. The ontology was evaluated through automated consistency checking, criteria-based and task-based evaluation. The AFPS-Onto fills the knowledge gap by providing a formal and shared vocabulary for the domain of AFPS design. This can promote knowledge reuse and sharing among professional engineers. In addition, the ontology can be used to develop knowledge-based systems to help design effective AFPS. Future effort can be made to develop ontologies of other control measures against fall from heights and combine them into a fall from heights ontology (FFH-Onto).

1. Introduction

Over the lifespan of a building, in particular during the construction phase, workers are required to work at heights [1]. As a consequence, managing fall from heights (FFH) constitutes an essential part of construction safety management. In fact, FFH is a leading direct cause of fatalities in the construction industry across many countries, such as the US [2], the UK [3], Australia [4], and New Zealand [5]. In Singapore, falls accounted for 35% of all workplace fatalities in 2015 and more than half of the falls were contributed by the construction industry. FFH also accounted for around 20% of the major injuries in Singapore workplaces over the past five years [6].

Preventing FFH is a significant concern for different stakeholders in the construction industry, including government agencies, clients/developers, contractors, health and safety professionals, and workers [7, 8]. There is a hierarchy of control measures for FFH, ranging from 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), administrative controls (e.g., working-at-height rules and procedures), to personal protection equipment (PPE). Although the hierarchy considers PPE as the least effective control measure, it is a must in situations where working conditions are difficult and other controls are not applicable. PPE for working-at-heights includes active fall protection system (AFPS), which is "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" [9]. It includes fall-arrest and travel restraint systems. A fall arrest system is designed to absorb the energy created by its user(s) during an accidental fall from heights. Typically, it consists of the following components: (1) full body harness, (2) connectors, (3) lanyard, (4) energy absorber, and (5) anchor [10]. A travel restraint system is a system that prevents its users from reaching an unprotected edge or opening [11]. In order for an AFPS to protect workers working at heights, an effective design is a prerequisite. Standards were developed to guide qualified persons designing effective fall arrest and travel restraint systems, such as Z359.6 [12], Z259.16-15 [11], and SS 607 [9].

However, inadequate designs of AFPS are still common. For example, Goh and Wang [13] evaluated eleven horizontal lifeline system (HLLS) designs in Singapore and found that none of the eleven designs was adequately endorsed or calculated. In addition, Hoe et al. [14] pointed out that current designs of AFPS by professional engineers (PEs) did not cover a wide range of critical areas and that some of design cases were not even accompanied by any calculations. In many of the designs, important factors were ignored such as dynamic forces created during a fall, the mobility needs of the workers, and safe access and egress. Poor designs of AFPS provide a false sense of security; injuries and fatalities could be caused when workers wrongly assume that they are under protection.

Inadequate designs can be in part attributed to a lack of knowledge (e.g., calculation methods). In practice, PEs tend to use different terms, jargon, and vocabularies in their designs, which makes knowledge reuse and sharing difficult. In addition, as in the case of other engineering designs [15], PEs can benefit from using knowledge-based systems (e.g., rule-based expert systems or probabilistic expert systems using a

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Bayesian network) when they design AFPS. These systems can offer recommendations and solve problems by using a rich body of knowledge in a domain of interest [16]. Developing an ontology is often considered an important starting point to construct knowledge bases for these systems [17]. Unfortunately, to the authors' best knowledge, no ontology has been developed yet to represent the knowledge of the domain of AFPS design. This often results in inefficiencies and inconsistencies in the design process of AFPS. Knowledge reuse and sharing are also significantly hampered.

Thus, this paper addresses the research gap by developing and evaluating an ontology (AFPS-Onto) for the domain of AFPS design in the building and construction industry. The ontology is aimed at providing a formal and explicit specification of a shared conceptualization of AFPS design domain. The ontology represents the domain knowledge of AFPS design and provides a computer understandable vocabulary for knowledge reuse and sharing and intelligent system development.

The rest of this paper is organized as follows: Section 2 presents a literature review of fundamental concepts of ontology, safety ontologies developed in the construction industry, and design of AFPS. Methodology used to develop the ontology is described in Section 3. In Section 4, we present the AFPS-Onto in terms of its generic ontological model, concepts, semantic relations, attributes, axioms, and coding. Evaluation of the ontology is described in Section 5. In Sections 6 and 7 we present conclusions and limitations and future work, respectively.

Table 1
Examples of ontology development methodology.

Methodology	Ontology development process
Grüninger and Fox's approach used in TOVE project [30]	(1) Identify motivating scenario; (2) define informal competency questions; (3) define the terminology of the ontology; (4) define formal competency questions; (5) specify the definitions and constraints on the terminology; (6) test the competency of the ontology
A skeletal approach [21,31]	(1) Identify purpose; (2) build the ontology (ontology capture, ontology coding, and integrating existing ontologies); (3) evaluation; (4) documentation; (5) guidelines for each phase
METHONTOLOGY [32]	(1) Specification; (2) knowledge acquisition; (3) conceptualization; (4) integration; (5) implementation; (6) evaluation; (7) documentation
a Simple Knowledge-Engineering Methodology (SKEM) [33]	(1) Determine the domain and scope of the ontology; (2) consider reusing existing ontologies; (3) enumerate important terms in the ontology; (4) define the classes and the class hierarchy; (5) define the properties of classes-slots; (6) define the facets of the slots; (7) create instances
The On-To-Knowledge methodology [34]	(1) Kick-off; (2) refinement; (3) evaluation; (4) ontology maintenance

2. Literature review

2.1. The concept of ontology

The concept of "ontology" has its roots in philosophy, where it is concerned with the nature of being and existence. In the past decades, it became a popular term inside a number of artificial intelligence (AI) communities, including knowledge engineering, natural language processing, and knowledge representation [18]. There are many definitions about what an ontology is and these definitions have evolved over the time [19]. Gruber [20] provided a popular one: an ontology is an 'explicit specification of a conceptualization' (p. 908). The conceptualization represents a specific world view on the domain of interest [21] and it is composed of concepts, attributes and relations between concepts. Neches [22] provided a descriptive definition which defines an ontology as "the basic terms and relations comprising the vocabulary of a topic area as well as the rules for combining terms and relations to define extensions to the vocabulary." An ontology, as a representation vocabulary, describes the domain knowledge in such a way that the specification can be interpreted by computer systems [23,24]. It captures an agreement on a domain conceptualization among stakeholders in the domain [25]. An ontology defines a shared vocabulary in a coherent and consistent manner with which queries and assertions are exchanged among people in a specific domain [20].

A number of methodologies for ontology building have been developed by researchers since the early 1990s. In 1990, Lenat and Guha [26] explored how to represent common-sense knowledge of the world for the Cyc project. In later years, a number of methodologies were proposed, as presented in Table 1. The British Standards Institution published an ISO standard to develop ontologies in 2015. The standard specifies the framework and rules for developing ontologies in the Web Ontology Language (WOL) [27,28]. A detailed review of all methodologies is beyond the scope of this paper. A systematic review of methodologies for ontology building can be seen in [29,19].

Ontologies have been developed in many fields (e.g., knowledge management, computer science, and artificial intelligence) for various purposes [24]. For example, in the domain of World-Wide Web, ontologies were developed to categorize websites and products for search engines (e.g., Google) and online shops (e.g., Amazon). Ontologies are used for knowledge connectivity, knowledge abstraction, and automation in knowledge processing in computer science. In artificial intelligence research, they are often developed for information integration, information retrieval, and expert systems [24,29]. Ontologies are also used as an important foundation for expert systems in which implicit knowledge from the axioms in an ontology can be derived for automated reasoning and solving different problems. In addition, ontologies are utilized to construct Bayesian networks for developing probabilistic expert systems [35–37]. As a computational artefact, ontologies provide computer systems with a computational framework of a particular domain [24]. By representing the domain knowledge in a machine-interpretable format, ontologies were developed and used by automated reasoning techniques to draw conclusions and solutions for different purposes in the construction industry [38–43].

2.2. Safety-related ontologies

In recent years, the roles played by ontologies in safety knowledge sharing and dissemination have been emphasized due to its ability to alleviate the interoperability problem in knowledge sharing and dissemination [44]. A number of safety ontologies were developed in the construction industry to formalize different types of domain knowledge and server for different specific purposes. The fundamental idea is that there is much to gain if safety data, information, and knowledge can be formalized based on a common set of ontologies that facilitates interoperability and reasoning process and improves efficiency of construction safety management. For example, Le et al. [45] developed a social network system for sharing construction safety & health knowledge (SNSS). The SNSS was aimed for better communication and representation for construction safety knowledge using a semantic wiki web and ontology approach. In addition, ontologies were developed to facilitate automated safety management, particularly job hazard analysis and management. For example, Wang and Boukamp [46] developed an ontology-based representation and reasoning framework for supporting job hazard analysis (JHA). The ontology represents and structures the knowledge about construction activities, job steps, and hazards. It forms a foundation for reasoning process which facilitates identification of potential solutions for hazards. In addition, Chi et al. [47] developed and used a construction safety domain ontology to match safe approaches identified in existing resources with unsafe scenarios. It aimed to reduce the level of human effort required in JHA and enrich the solution space by serving as initial references. More recently, Zhang et al. [48] proposed a construction safety ontology to formalize