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Workforce location tracking to model, visualize and analyze workspace requirements in building information models for construction safety planning

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ABSTRACT

Safety as well as productivity performance in construction is often poor due to congested site conditions. We lack a formalized approach in effective activity-level construction planning to avoid workspace congestion. The purpose of this research is to investigate and prototype a new Building Information Modeling (BIM) enabled approach for activity-level construction site planning that can pro-actively improve construction safety. The presented method establishes automated workspace visualization in BIM, using remote sensing and workspace modeling technologies as an integral part of construction safety planning. Global Positioning System (GPS) data loggers were attached to the hardhats of a work crew constructing cast-in-place concrete columns. Novel algorithms were developed for extracting activity-specific workspace parameters from the recorded workforce location tracking data. Workspaces were finally visualized on a BIM platform for detecting potential workspace conflicts among the other competing work crews or between material lifting equipment. The developed method can support project stakeholders, such as engineers, planners, construction managers, foremen and site supervisors and workers with the identification and visualization of the required or potentially congested workspaces. Therefore, it improves the foundation on how decisions are made related to construction site safety as well as its potential impact on a productive and unobstructed work environment.

1. Introduction

Traditional safety planning mainly relies on manual observation, which is labor-intensive, time-consuming, and potentially highly inefficient. The link between planning for safety and work-task execution is often weak: for example, many contractors use two-dimensional drawings or field observations to determine hazard-prevention techniques [1,2]. The resulting safety plans are often error-prone due to subjective judgments of the available decision makers. Currently, historical workspace information for an activity and the corresponding contextual information depicting the condition under which the activity is accomplished are not stored. Hence, workspace planning for work activities in construction planning is often overlooked.

Although knowledge is typically transferred from one project to the next, this important task could be optimized, especially when experienced field staff is hired elsewhere. These circumstances lead to workspace congestion often at the beginning of projects. This may then largely impede worker safety, health, and productivity on a construction project. There is a need for an approach to collect, formalize, and reuse historical activity-specific workspace information.

The selected approach, other than previous approaches [1], describes an empirical study method that collects the active workspace, obtains its geometric parameters, visualizes the workspace, and detects workspace conflicts in building information models (BIM). A BIM-based application prototype for workspace visualization is eventually presented which demonstrates how this approach can assist activity-level construction planning.

This paper is structured as follows: Section 2 reviews workspace representation techniques and existing studies on the application of advanced location tracking technology in the construction industry. Section 3 presents the objective and scope of this study. In Section 4, workspace conflict taxonomy and representations are presented. The computation of workspace parameters based on location tracking data and visualization of workspace in BIM are explained in Section 5. Workspace conflict detections are discussed in Section 6. Section 7 presents a case study to the proposed workspace conflict detection using the developed prototype system. A summary of the contributions and discussions about future research needs is presented in the final section of this paper.

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2. Background

2.1. Construction workspace representation

Experts witness another phenomenon on construction sites: fast tracking and schedule compression create task overlaps on construction sites due to pressure for completion on time. This conflict occurs often, because multiple concurrent tasks compete for the limited workspace on site. Dealing with the planning and execution of simultaneous tasks and their workspaces is a main challenge that has been addressed in multiple workspace planning studies.

For this reason, 4D (3D and time) representation and analysis of workspaces for construction activities during the planning, scheduling, and eventually already at the design phase, are encouraged, since they can minimize workspace congestion and conflicts which frequently exist at construction sites. It also keeps the construction personnel working safely and productively.

Thabet and Beliveau [3] and Riley and Sanvido [4] presented a scheduling model that incorporates workspace constraints in the scheduling of repetitive work in multistory buildings. Their model proposed a method to define and quantify several workspace parameters (space demand < physical space demand and surrounding space demand > and space availability). Akbaş [5] described a geometry-based modeling and simulation approach called geometry-based process model (GPM) for modeling and simulation of construction processes based on geometric models and techniques, which provides improved modeling and simulation techniques for construction operations and more effective use of geometry for construction practice and research. However, GPM relies on the user to define the crew parameters and sequences to generate the activities and simulate the process given these parameters. Akinci et al. [6] firstly developed space templates linked to construction method templates to enable users to define the space requirements of different construction methods; secondly, they developed a prototype system called the 4D WorkPlanner Space Generator (4D SpaceGen) [7]. It uses the spatial requirement knowledge, captured generically in the space templates, to automatically generate the project-specific instances of spaces; thirdly, they formalized time–space conflict analysis as a classification task and addressed these challenges by automatically (1) detecting space conflicts, (2) categorizing the conflicts, and (3) prioritizing the multiple types of conflicts between conflicting activities [8]. However, their work did not consider the material travel path nor defined the required workspace. Choi et al. [9] classified workspace by its function and its relocatability to further represent different characteristics of a workspace. The latter one enables better integration of the workspace requirement and their planning processes. One limitation of this work is that enormous efforts are required to prepare the input data such as detailed construction schedules.

Dawood and Mallasi [10] applied entity-based 4D CAD technology for detecting workspace congestion to help identify potential safety hazards on-site using critical space-time analysis (CSA) in 4D visualization. The proposed CSA associates certain visual features for workspace planning with the workspace competition. The PECASO (Patterns Execution and Critical Analysis of Site-space Organization) prototype was developed to encapsulate and evaluate the outcome of the CSA. Kassem et al. [11] created an Industry Foundation Class (IFC) compliant 4D tool for workspace management. Haque and Rahman [12] linked a 3D BIM model with the schedule and construction space requirements, and simulated the 4D model to detect whether there is any space conflict during the activities. Jongeling et al. [13] used distance between the different types of work as an important factor in safe and productive work execution, by manually extracting 4D spatial content from 4D CAD models. Zhang and Hu [14] proposed an integrated solution of analysis and management for conflict and structural safety problems during construction. Moon et al. [15] generated workspaces using a bounding box model and an algorithm in order to identify schedule and workspace conflict. Moon et al. [16] realized a BIM-based active simulation system using genetic algorithm (GA) process for an alternative schedule to minimize the simultaneous interference level of the schedule-workspace. Su and Cai [17] presented a life-cycle approach to workspace modeling and planning. However, no scientific method is provided for generating the space requirement more rapidly, or eventually automatically. A summary and their shortcomings of some of the applied methods in recent 3D workspace management studies are listed in Table 1.

Many existing and well-executed studies focused on critical space analysis and space planning which use workspace as input criteria in their developed systems. However, neither one of these approaches has provided reliable spatial information since their workspace input are either estimated based on the authors' background or experience, or it requires a user to determine their own input values. Riley and Sanvido [18] concluded therefore, that different materials and activities have repeating (predictable) space needs from one project to the next. The challenge is to find more appropriate ways to represent the workspace and to suggest acceptable workspace parameters.

2.2. Resource location tracking in construction

Safety risks on construction sites are often closely related to the proximity of construction materials, equipment, and workers to nearby hazards [19,20]. Some of these are explicit, for example, the risk of falling from the leading edge of a concrete slab floor [2]. Some of the risks have also been defined and quantified in Hallowell and Gambatese [21] and Rozenfeld et al. [22]. Some researchers recommended using positioning devices to locate construction resources and deliver pro-active information in real-time to mitigate a worker from entering a hazardous area or performing unsafe or unhealthy work activities [23–27]. While some research investigated the error performance of positioning and path planning technology [28–30], Maalek and Sadeghpour [31] studied the performance of an Ultra Wideband (UWB) tracking system in static mode under conditions that commonly occur on construction sites. They proved that the accuracy of commercially available real-time location tracking technology could be used to display resource location in information models. They further indicated that "the accuracy of the system could be used in the definition of the size of buffer zones in construction site safety applications". Many technologies exist today that might offer a solution for pro-active real-time hazard detection and warning based on pre-defined and geo-referenced hazard zones. Examples of research using location tracking technology for safety purposes are small GPS data loggers [32] and UWB [29,30]. Although each of the proposed technology has shortcomings and may only work under certain conditions in the harsh construction environment, they can gather valuable activity-based location data from resource (worker, equipment, and materials) movements. Once data is gathered and processed using computer algorithms, the resulting information has the potential to support workspace modeling and visualization.

A construction site is a very dynamic environment in which workspace related to construction activities changes continuously. The locations and volumes of these spaces change in three dimensions and over time, according to project-specific design data. Unless advanced automation or lean approaches are applied, congestion among various work activities can often not be eliminated, which can lead to additional safety or health hazards [33]. Hence, there is a need for more effective activity-level construction safety planning.

3. Motivation to use novel technology and methods

According to US Occupational Safety and Health Administration (OSHA), "routes for the suspended loads should be pre-planned in order to ensure that no worker has to work directly below a suspended load (except for those workers who must hook up or unhook the load, or work on the initial connection of the steel members)." [34]. From 1992 to 2006, 307 crane accidents in the private U.S. construction industry sector killed 323 workers [35]. In 2006, cranes contributed both as