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Real-time resource location data collection and visualization technology for construction safety and activity monitoring applications

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ABSTRACT

Data to field operations of construction resources (personnel, equipment, materials) is vast, but the effort of collecting, analyzing, and visualizing is hardly ever taken. One main reason that limits higher quality in project site management decision making especially in resource intensive and complex operations is access to real-time information and subsequent technology that enables effortless data collection, processing, and visualization. Although recent developments in remote data sensing and intelligent data processing supplement manual data recording and analyze practices, few data on visualization tools in construction exist that gather data from dynamic resources and stream it to a field-realistic virtual reality environment in real-time. State-of-the-art technology in the field of real-time data collection and visualization is reviewed. A novel framework is presented that explains the method of streaming data from real-time positioning sensors to a real-time data visualization platform. Three case studies are presented which highlight its methods for recording data and visualizing information of construction activities in a (1) simulated virtual construction site, (2) outdoor construction setting, and (3) worker training environment. The results demonstrate that important construction information related to both safety and activity in field operations can be automatically monitored and visualized in real-time, thus offering benefits such as increased situational awareness to workers, equipment operators, or decision makers anywhere on a construction project or from a remote location.

1. Introduction

The distributed nature of construction project information and the presence of multiple teams performing on site are well known characteristics of a typical construction project. Communication of essential information among construction project stakeholders is considered a key for successful construction engineering and management. Traditionally, an enormous amount of site information has been communicated among project team members by means of paper-based documents including two-dimensional drawings or verbal communication. A significant deficiency in the traditional information delivery process has been that the project team is not always in the position to make rapid and correct decisions because of unavailable or insufficient information [1].

For the purpose of making more timely and more accurate decisions during construction, at multiple hierarchical levels and timescales, and for multiple stakeholders and entities, a deeper understanding of construction activity information is needed in real-time and additionally in a visually appealing format. In addition, practitioners believe that a more effective use of gathered and distributed real-time site information would generate new knowledge that can assist project stakeholders in making more effective and efficient decisions on-site or even from a remote location [2].

Important site information such as the location of construction resources (personnel, equipment and materials) – including their inter-relationships and temporal information on specific work tasks – is currently mostly manually monitored and recorded [2]. Such observation tasks require typically experienced observers but often such observations remain error prone as they are very labor intensive, time-consuming, and potentially subjective. Moreover, manual observations are made through the viewpoint of the observer and the particular perspective might either not be the best one. Another limitation of manual data collection is that later, at the data analysis stage, the perspective of the observer can often not be shared with other project team members. These limitations of current practices can become a bottleneck for fast and accurate decision making on a busy construction site. Especially, large capital facility projects with hundreds or thousands of resources being present on the construction site require more oversight. One of the primary application areas that would benefit from real-time resource location tracking and visualization is safety and construction site monitoring. Although manual observations have distinct advantages which might not be replaced soon, they also could benefit from such a new technological approach.

Effective construction safety and site monitoring start at the front-end of a project. Several approaches have been taken in the past to coordinate construction design and planning with site organization and layout. One way of finding potential clashes or hazards is using walkthroughs in virtual reality (VR) models. VR is a method of

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visualization which aligns virtual objects with the ones in the real world. Many applications of VR technology have been found in building science covering both project design and construction operation levels. Immersive VR systems also have wide applications in practice and education of architects, engineers, and contractors who deal with the design and construction of buildings. The main reason of its rising implementation is that (immersive) VR has the unique capability of giving users a sense of presence and scale, as if they were observing a realistic world. By immersing the user in a computer generated synthetic environment, VR learning and training offers an active learning experience where the user is in control and is required to deliberate proper actions from a safe and secure observation point. VR also facilitates the understanding of complex construction processes by the interaction within the VR environment [3].

Tracking and visualizing dynamic resource data in a field-realistic virtual environment in real-time have additional benefits to a project team [2]. For instance, spatial constraints of a work environment, workers themselves and their safety behavior, can be improved once their inter-related risks (e.g., hazards in the work environment) have been identified and assessed properly. Such risks are often caused when workers are set to work in an unsafe workplace. Another reason is that workers are pushed to work 'near the edge' and beyond the zone of control or recovery [4].

One alternative is to prevent putting workers in such risky environments by educating and training designers or planners at the front-end of projects [5]. As they can eliminate most hazards before workers are sent to the site to carry out work tasks, it would be useful for them to have as much information on risks available as possible. In particular, information what impact design has on hazards would greatly benefit Prevention through Design (PtD) concepts. One example of the data which might provide such information for construction site layout design is trajectory data of resources from the construction site embedded in spatial terrain models. Monitoring and analyzing the paths of workers and equipment in a design model may give further conclusions on how to change or correct design or at least plan construction work more safely.

During the operation phase, the same data visualization – if performed in real-time – could then benefit safety engineers and managers to react potentially in real-time to an incident. Coordination of search and rescue efforts could also become more effective. Another potential benefit of real-time data gathering and visualization is that data can be documented and used afterwards to establish more efficient and effective safety best practices, education, and training methods.

This paper focuses on one of the key research challenges in real-time pro-active construction safety and site activity monitoring: gathering and processing construction resource data in real-time and visualizing relevant safety and activity performance information to a user (decision maker) in real-time. After a literature review, remote sensing and visualization technologies are introduced that monitor, record, and visualize safety-critical data of construction resources (personnel, equipment, and materials) in real-time. A realistic and rapid virtual visualization environment technology will be introduced. The developed real-time spatio-temporal tracking and visualization framework and results to three case studies follow before the paper finishes with a conclusion and an outlook of future research.

2. Background in data visualization technology

Many efforts have implemented virtual environments for the purpose of visualizing architectural designs and facilitating building construction and project management level. The use of virtual reality (VR) mockups to replace existing physical models was investigated by Fernandes et al. [6] for a courthouse project. Another study was conducted to describe the barriers that impact the practical implementation of VR, such as management support, degree of business competition, coordination of design resources and participation of end users [7]. An immersive large scale VR projection system was developed for students in the architectural engineering program in order to experience and experiment with three-dimensional (3D), full scale virtual models of construction projects [8]. VR applications were also used in an architectural design studio to coordinate and critique student work within a collaborative virtual environment (CVE) [9,10]. A Virtual Reality Modeling Language (VRML) [11] was developed to represent the steel structure and construction equipment with online project information access.

Visualization technology has been a widely applied tool even in construction management. Virtual construction allows stakeholders to detect and inspect construction problems early in the design phase and enables contractors to manage projects more efficiently [12–15]. 4D graphics for construction planning and site utilization were developed to assist planners to deal with daily activities and site management [16]. Akinci et al. [17] also worked on site layout optimization. Koo and Fischer [13] suggested that a 4D VR model increases the comprehensibility of the project schedule and allows users to detect potential problems such as scheduling conflicts prior to the construction. They have suggested that a planner using 4D simulation is likely to allocate resources more effectively. The use of 4D CAD also assists the planner in avoiding schedule conflicts, examining constraints, and evaluating alternative construction methods.

As the literature review shows, most of the recent research focused on cost, scheduling, and the extent of architectural design. VR technologies have since then been implemented successfully in Building Information Models (BIM) and resulted in significant cost savings in particular when applied to complex projects. To date, there is little VR research focusing on factors such as real-time pro-active safety and activity monitoring, or any analysis that focuses on the construction task level. Few VR tools have so far addressed adequate real-time data visualization. As other research literature states "a clear agenda for using real-time construction site data collection and visualization is missing" [2].

Real-time safety hazard recognition, reporting, and visualization prompted researchers to investigate these topics at the earliest possible stage in the construction process [18]. Traditional safety hazard identification in construction has been using a combination of site drawings and project schedules. Up to today, very often decisions are being made based on manual/visual site inspection(s). Since field drawings are mostly in 2D, safety managers have often difficulty understanding the spatial constraints of the work environment [19].

The application of VR has so far not been very common at the construction task level since most VR models are based on simulated data or prerecorded data. Such models or data cannot represent or reproduce the changing nature of a construction site. In addition, existing VR tools require expert knowledge to handle and customize the intensive graphical and dynamic characteristics of construction task modeling [20]. Immersive VR at the construction operational level started focusing on displaying resources (personnel, equipment, materials, terrain, building objects) over time. Kamat and Martinez [21] formalized a descriptive language to facilitate automated communication of simulated dynamic construction scenarios that can visualize construction operations in a 3D virtual environment. Kamat and Martinez [22] developed dynamic 3D visualization and simulation of articulated construction equipment, such as a crane or excavator, by using the principles of forward and inverse kinematics. Their research proposed an approach to achieve smooth, continuous motion of virtual construction resources based on discrete and simulated information. Recent research investigated the generic and scalable techniques to accurately represent 3D motion paths. The VITASCOPE visualization system is a dynamic animation of operations and applies discrete-event simulation [23]. Rekapalli et al. [24] presented accurate and high-speed animation of such simulated models.

Apart from the implementation in the engineering practice, many efforts have been invested in the application of information technology especially advanced VR and VE technologies in building science