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On-site visualization of building component erection enabled by integration of four-dimensional modeling and automated surveying

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This research develops a new methodology for seamless integration of automated construction surveying with four-dimensional (4D) modeling in order to improve current practices of building component positioning and erection in terms of efficiency and quality. The building production models are represented in 4D and generated in consideration of construction engineering constraints, such as lifting capacity of tower cranes, construction method and activity sequence. The surveying data include identification, surveying time and coordinates of a limited quantity of tracking points that are marked on a building component. The data are processed using a special algorithm to derive transformation matrices, which encode movements and rotations of a solid object in the 3D space. As a result, the 3D model of the building component is updated to mirror its actual motion in the site during installation operations. Furthermore, by comparing the as-designed model and the actual model of the building product, any deviations between them are determined in terms of position offsets and rotation angles, which facilitate follow-up adjustment operations. A software system named as 4D-PosCon (acronyms of four-dimensional positioning controller) was prototyped based on the proposed methodology. Laboratory experiments were designed and carried out, validating the proposed methodology and demonstrating the prototype system of 4D-PosCon. In conclusion, the resulting 4D visualization is effective to facilitate positioning control in erecting a building component by providing intuitive perception and accurate comprehension of the relative orientation and position of the building component in reference to its final as-designed state.

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1. Introduction

Locating and positioning building components in the three-dimensional space of a construction site is the fundamental construction operation [1]. Accurate positioning of bulky building components such as structural steel members are labor-intensive, highly repetitive and time consuming tasks, which are normally conducted by laborers exposed in a potentially hazardous environment like an elevated location [2,3]. In an American Institute of Steel Construction report, decreasing fabrication and erection time for steel frame building while increasing the safety of workforce during construction are identified as two crucial issues on automated steel construction, while time required to erect a steel frame structure needs to be reduced by 25% for the steel construction industry to remain competitive [3]. At present, it is imperative to improve positioning control practices during the process of erecting bulky building components, aimed at better productivity, enhanced safety and higher quality.

On the other hand, automated reality capturing technologies and computer technologies have been rapidly advancing, making construction sites more intelligent and integrated [4]. In recent years more and more construction projects have used three-dimensional/four-dimensional (3D/4D) models to support management tasks [5]. While these models contain accurate spatial information of the building products to be constructed, when it comes to the setting of an actual construction field, those spatial models have not yet found much value-added applications [2]. One main reason is that these models lack the integration of "reality" information enabled by cost-effective methodologies so as to materialize seamless integration with automated reality capturing technologies [6].

This research develops a new methodology for integration of automated construction surveying with 4D modeling in order to improve current practices of building component positioning and erection in terms of efficiency and quality. Given a building component being installed, any deviations between its actual position state and its as-designed final position state are computed according to site surveying data and visualized in a 4D system. 3D models for both the current site state and the final as-designed state are contrasted in the same screen. This enables site engineers to make

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fast decisions on how to correct the positioning of the building component during erection, and to reexamine correction effects with 4D models as soon as adjustment actions are taken.

This paper is organized as follows: first, related research found in the literature is reviewed and discussed. Next, the proposed 4D visualization methodology is described step by step, illustrated with a numerical example. Based on the new methodology, a software system called 4D-PosCon is prototyped with user-friendly graphic user interface designed to cater to practical needs identified from site studies. Finally, laboratory experiments are conducted to verify the feasibility and effectiveness of the proposed methodology. Conclusions and future research directions are given in the end.

2. Literature review

The three research areas related to the presented research are reviewed in this section, namely: (1) automated data collection technologies; (2) application of 3D/4D visualization technologies in construction; and (3) spatial integration in construction.

2.1. Automated data collection technologies

The advancement and wide application of automated data collection technologies make construction sites more intelligent and integrated. As envisioned by the Fully Integrated and Automated Technology consortium, materials, components, tools, equipment, and people will become elements of a fully sensed and monitored environment [4]. Automated data collection technologies applicable to construction sites vary in functionality, accuracy, cost and application scope. Currently available technologies are reviewed in order to select the tracking and positioning technology that lends itself well to the application of structural component positioning control during erection.

Global positioning system (GPS) is available in most locations of the world to provide 3D positioning of latitude, longitude and altitude to anyone with a GPS receiver. GPS is particularly appropriate for the outdoor position tracking, such as tracking user's positions in open sites [7], locating construction materials on industrial projects [8,9]. However, GPS signals emitted by the satellites can be easily blocked and deflected on a construction site [10], compromising the reliability and accuracy in positioning resources on a construction site. The positioning accuracy provided by commonly available GPS is in order of a few meters, while high precision GPS solutions with achievable accuracy in millimeters, such as real-time kinematics (RTK) GPS, are expensive in terms of application cost, entailing complicated system setup and calibration [11].

Ultra-wideband (UWB) is a more recent commercially available radio technology that can be used at very low energy levels for short-range high-bandwidth communications on a wide spectrum of radio frequencies. It can be used for precision locating and tracking of construction laborers, equipment, and materials in semi-open areas [12]. Although UWB has the advantages of "see-through-the-wall" positioning with higher accuracy and lower uncertainty (0–50 cm according to [13]), it is a relatively expensive technology and requires significant time and effort to deploy the hardware (the hub and receivers) around the coverage area [13].

Radio-Frequency Identification (RFID) is one of the most explored and matured technology with successful applications in identification and localization of construction components [10,14], progress management [6] and construction quality inspection and management [15]. RFID does not require (1) line-of-sight, (2) close proximity, (3) individual readings, or (4) direct contact, and a RFID tag features data entry and access at any time and data storage capability [16]. The main factor that impedes the application of RFID for positioning structural components during installation lies in RFID's low positioning accuracy, which can only indicate approximate locations of building components on site [17].

Laser scanning is another reality capturing technology that uses a laser scanner to capture vast amounts of measurements of points (point clouds) in the targeted object and its vicinity [16]. Nevertheless, it is computationally intensive and difficult to filter various sources of noises and register multiple scans in generation of a more comprehensive, accurate set automatically [16,18].

Photogrammetry originated from the discipline of surveying and is capable of extracting input data from two-dimensional photo images and mapping them onto a three-dimensional space [19]. However its accuracy is largely dependent on the quality of the camera used, the quality of the photos taken and the functionality of the photo-processing software applied. For an off-the-shelf digital camera with fixed focal length and eight megapixel image resolution, the achievable accuracy level was found to be in the order of one to two centimeters in comparison with a conventional measurement tape [19].

Nowadays, total stations, have replaced transits and theodolites and increasingly become the predominant instrument used in surveying practices [20]. A modern robotic total station functions like a surveying robot capable of automatic target tracking controlled by pre-programmed surveying procedures. With the programmable interface provided, the coordinates of a limited quantity of points can be automatically collected in a certain frequency and with high accuracy in order of a few millimeters, which makes a robotic total station ideal for positioning control during the installation of building components. From our site investigation which was carried out in 2007–2008 based on a high-rise building site (the "West Tower" in Guangzhou, China), it was observed total stations were used to control positioning in erecting bulky structural steel elements, yet automation and 4D visualization functionalities as desired by the site people were not realized.

2.2. Application of 3D/4D visualization technologies

In recent years, 3D/4D models have been widely applied to support a wide range of construction management tasks, such as construction planning [21], constructability review [22] and site layout planning [23]. However, their applications have been largely focused on architectural debriefing and construction planning in early project stages. During the construction stage, crucial site activities lead to the creation of physical structures and elements; thus, visual information is required to understand and communicate their own complexities and their relationships to existing structures or elements [24]. Hence 3D/4D visualization technologies have significant potential to facilitate a variety of construction tasks at the operations level, given cost-effective methodologies are available to incorporate real site information. Chin et al. reported research on integration of RFID and 4D CAD for progress management of structural steel works in a high-rise building [6], showing the potential of the next generation 4D system which integrates 4D models with on-site data. In the present research, we extend the current state of knowledge in 4D modeling by addressing the application-level integration of 4D models and automated surveying by a total station, aimed at improving current practices of building components positioning and erection.

2.3. Spatial integration in construction

Spatial integration in construction refers to research efforts of synthesizing various technologies for spatial data collection in construction operations so as to improve productivity, quality and safety of the construction process. Examples include the integration of real-time position measurements with computer aided design (CAD) [1], merging spatial design data with the digital model of equipment working on implementing the design [2], and real-time updating the

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