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4D CAD model updating using image processing-based construction progress monitoring

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ABSTRACT

For a four-dimensional (4D) computer-aided design (CAD) model to be useful for users throughout a construction project, the model must be updated in a timely and accurate manner during the construction. Only when it has been properly updated can the 4D CAD model reflect the real progress of a construction site to inform managerial decision making. However, updating a 4D CAD model is time-consuming and labor-intensive because the full updating process, from site data acquisition to 4D model regeneration, is typically conducted manually. This difficulty in updating a 4D model discourages industry practitioners from actively adopting 4D models. This paper presents an image processing-based methodology for the automatic updating of a 4D CAD model. Characterized by 3D CAD-based image mask filters, color-based noise removal, and area-based progress calculation, the image processing approach provides as-built schedule information. The schedule information is then automatically integrated with an existing 3D CAD model in batch-processing modes to produce the updated 4D CAD model. The proposed methodology was applied and verified in a cable-stayed bridge construction project and is expected to facilitate the wider use of 4D CAD models in the construction industry.

1. Introduction

Four-dimensional (4D) computer-aided design (CAD) – a combination of three-dimensional (3D) CAD models and their corresponding time (schedule) information – is a promising technology that has been developed to aid in effective construction management. 4D CAD can visualize construction projects on a range of management levels (e.g., the project, activity, and operation levels) for the purpose of identifying problems related to construction design and planning. For example, a 4D CAD model of a construction activity sequence enables engineers to conduct collision checks, work space analyses, and schedule evaluations prior to construction [1]. The improved understanding of a construction project provided by a 4D model allows engineers to proactively manage their projects with enhanced communication among construction participants.

Despite the advantages of 4D CAD, inefficiency in the 4D model development process has prevented its widespread utilization in the construction industry [2]. Generally, the development of a 4D CAD model consists of the following steps: 3D CAD model generation, construction schedule development, and the creation of relationships between construction schedule and 3D CAD model. Among these three processes, 3D CAD model generation has improved substantially as a result of parametric modeling studies, interoperability improvement studies, and diverse 3D library developments. However, the schedule development and relationship creation processes still require significant improvement to expedite the generation of 4D models.

The process of schedule development involves regular updating of the original construction schedule. For the original schedule to be useful to construction engineers throughout the construction project, it should be regularly revised based on up-to-date progress information during construction. Unfortunately, the revision (i.e., schedule updating) process is time-consuming and labor-intensive because the current practice of site data acquisition relies heavily on manual observation. The process of relationship creation between a schedule and a 3D model also requires significant time and attention and typically requires users to individually match each 3D component to its corresponding time information. These manual processes of observation and matching are naturally error prone, especially when for large-scale construction projects. Therefore, automated and more efficient methodologies are required to aid construction engineers in developing and updating 4D models.

Recent studies have attempted to automate the processes of construction site monitoring using various sensing technologies, such as radio frequency identification (RFID) [3,4], 3D laser scanning [5,6], and digital image processing [7,8]. These efforts, along with other studies, have demonstrated that advanced sensing technologies can automate the traditional construction monitoring process. In particular, digital image processing has been shown to have great potential to replace the existing practice of progress monitoring as long as high-quality 3D site information is not required. Neto and Arditi [9]

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used red, green, and blue (RGB) color space to identify a structural component of a bridge. To identify columns in a building, Wu et al. [7] used 3D CAD-based image processing techniques coupled with Canny-edge detection and watershed transformation. Zhu and Brilakis [10] used machine learning techniques, such as artificial neural networks and support vector machines, to detect concrete regions in construction site images. Son et al. [11] suggested an optimal combination of color space and machine learning algorithms through a comparative analysis of three machine learning algorithms in two non-RGB color spaces. The success of these studies guided the authors of the present study to consider digital image processing as a strong candidate for the automated monitoring of construction progress.

The purpose of this study is to develop an image processing-based methodology for the automated updating of a 4D CAD model. The scope of the study includes almost the entire cycle of 4D CAD model updating, from site data acquisition to 4D model development. However, the construction objects of interest are limited to the structural components of a deck segment in a cable-stayed bridge because the proposed methodology is applied to a cable-stayed bridge project for its verification. This paper begins with literature reviews of previous studies on 4D CAD applications in the construction industry to identify the difficulties associated with the development process. Automated site-image acquisition and processing techniques for progress monitoring are then suggested, followed by a method to automatically integrate schedule information with a 3D CAD model. After a case study involving the actual construction of a cable-stayed bridge is presented to verify the proposed methodology, research contributions and recommendations are summarized.

2. Research background and objectives

There have been various research efforts to identify the merits and limitations of 4D CAD technology in the construction industry. Koo and Fischer [12] studied the feasibility of 4D CAD in a commercial building construction project. Ma et al. [13] applied 4D CAD to construction management with a focus on dynamic site layout. Kang et al. [14] conducted an empirical study on the merits of web-based 4D visualization systems. Mahalingam et al. [15] evaluated the acceptability and usefulness of 4D CAD based on two infrastructure and two commercial projects. Kim et al. [16] suggested three different levels of detail for 4D models according to the different needs of civil infrastructure projects. Park et al. [1] investigated the applicability of 3D and 4D CAD over the entire lifecycle of construction projects. These previous studies have demonstrated that 4D CAD is an effective visualization and analysis tool for construction management, and the need to expedite the slow process of 4D model development was also identified as an important subject of future research.

Advanced construction progress monitoring and efficient schedule data preparation are the two major areas of improvement for 4D model development. Various studies have been conducted on these topics using a range of sensing technologies. Chin et al. [17] used RFID technology to develop 4D models for the progress monitoring of structural steel projects in high-rise buildings. Golparvar-Fard et al. [18] used unordered site images to develop 4D as-built models integrated with 4D as-planned models. Turkan et al. [6] combined laser scan data with a 3D model and schedule information to track construction progress in the form of a 4D model. The method proposed by Turkan et al. [6] automatically updated the 4D model with new site information, resulting in an automated progress feedback loop. Using digital image processing as the main methodology, the present study further pursues the study of progress feedback loops demonstrated by Turkan et al. [6].

In general, an image-capturing device is likely to produce less accurate data than those obtained from high-end 3D laser scanners. Point cloud data provided by laser scanners often have high-resolution 3D coordinate information that a typical image sensor, such as a 2D camera, is not capable of producing. However, image data have their own advantages. First, a typical imaging device is affordable enough to install easily on site and record construction activities throughout the project. Second, image data normally have color information that can be used in a variety of ways for nuanced site representation. Third, less computational time is required to process image data into a form of information than is needed to record and process 3D coordinate data. Thus, as long as an imaging device has a clear line of sight to the construction site and the site is properly configured in the obtained image, digital image processing can be an effective and viable solution for monitoring construction projects. The purpose of the present study was to develop an automated 4D CAD updating methodology using image processing-based construction progress monitoring. The specific objectives of the study were to automate the processes of identifying construction progress, developing as-built schedule data, and integrating schedule information with a 3D model.

3. Image processing-based automated project scheduling

Fig. 1 illustrates the overall procedure for image processing-based automated project scheduling. The first step of the proposed methodology is to acquire image data of the construction site (Fig. 1(a)). Camera selection and installation guidelines for high-quality site images are presented in Section 3.1. Second, construction progress is identified by various image processing techniques (Fig. 1(b)). Objects of interest are recognized using 3D CAD-based image mask filters, and useless objects (noise) are removed using the hue, saturation, and value (HSV) color space. The progress information obtained through the image processing is used to generate an as-built construction schedule for 4D CAD. Finally, the 4D CAD model is updated using the 3D CAD model of the construction components and the construction schedule data (Fig. 1(c)). The following sections provide details of the image processing-based progress monitoring methodology for 4D CAD.

3.1. Image analysis for progress monitoring

Construction site image acquisition is an important first step in progress monitoring. Depending on the quality of the site image data, results from image processing-based progress monitoring may vary. Therefore, effective guidelines for camera installation and image data management are crucial to the success of the subsequent image processing in the construction industry. First, the camera location should be high enough to minimize line-of-sight interruptions to the view of the construction site. If the camera is immobile, a sufficiently elevated position increases the chance of stable and continuous image data acquisition. Second, the camera should be programmable and equipped with a pan, tilt, and zoom (PTZ) movement function. The PTZ function, coupled with programmable abilities, allows construction engineers to freely view and record particular activities in a customized fashion. Third, the camera must be effective at transferring data. Wired or wireless local area networks with internet connections are preferred for the transfer and saving of acquired site-image data to a main server.

Once site images are acquired and saved, they are ready to be processed for progress monitoring. Fig. 2 shows how construction images are analyzed to produce construction schedule information using a deck segment of a cable-stayed bridge as an example. The RGB image in Fig. 2 is the original color image showing the installation of two edge girders (vertical members) and three floor beams (horizontal members). The image processing task is now to separate the five structural components from the background region and from one another so that each component can be independently recognized. However, there is always a chance that the line-of-sight to the objects of interest may be blocked. As shown in the RGB image in Fig. 2, moving equipment, such as a derrick crane, may block the line of sight, making it difficult for the camera to acquire quality images. To ensure the