A Real-Time 4D Augmented Reality System for Modular Construction Progress Monitoring

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Abstract –

Construction monitoring plays a vital role in modular construction practice, since faulty installation of individual parts could incur significant delays and extra cost to the project, modular construction eagerly requires a real time progress monitoring. Previous researchers tended to get as-built site data back at first, like making cloud points model or taking photos, and then use it to compare with as-designed BIM model. Such an approach cannot find any potential problem before it happens and will still bring unexpected economic loss and schedule delay. In converse thinking, this paper developed a real time 4D AR system for modular construction progress monitoring, which uses the as-designed AR model to compare with the as-built site, in which a markerless AR registration method is established to link the 4D BIM data with the as-built ones directly. In addition, mock up components are used as a scale model to validate the system. The result indicated that, the system can facilitate users to avoid possible errors by giving helpful assembly sequence monitoring and powerful tool for schedule control.

Keywords –

Construction progress monitoring; Modular construction; 4D BIM; Augmented reality

1 Introduction

Construction progress monitoring has been regarded as a critical successful factor in a construction project. Timely construction progress monitoring brings efficacious manner and helpful decision-making to management team members such as construction manager and on-site supervisors. In a modular construction project, every unit gets its own assembly sequence and position, any wrong assembly would definitely bring project delay and extra cost for rework. Thus, compared with onsite project, real-time construction progress monitoring between as-planned and as-built progress is much more important to modular construction.

1.1 BIM in Construction Progress Monitoring

Building Information Modelling (BIM) can be expected to help the management team in a modular construction project to make decision for assembly sequence simulation and work plan control before constructing. It has been proved that 4D BIM (3 dimensions digital model with timeline) gives effective support for construction scheduling and site monitoring by updating onsite data and comparing with 4D BIM models (Hamledar et al., 2017). Another method via using 4D BIM in concert with 3D data obtained by remote-sensing technology was proposed, in which continuous scanned data are obtained and compared with BIM model, but it assumed that there is no deviation from original construction plan (Kim et al., 2013). Partial point cloud device equipped in construction workers' protection helmets was also used for continuous construction progress monitoring, and the device can get as-built 4D BIM model which can be compared with 4D as-designed BIM model to check current progress status, but it needs workers to go through project site to collect data, and it is possible to miss cloud point data of some corners (Zoran et al., 2018). Also photos taken by UAV can be used to make cloud points model for progress monitoring, comparison between as-built and as-planned is visualized via using a corresponding point cloud and source image with re-projected geometry (Braun et al., 2018).

1.2 AR in Construction Progress Monitoring

On the other hand, Augmented Reality (AR), which adds computer generated objects into real world images, links 4D BIM data with real construction site and bring systemic and comprehensive progress monitoring and control (Lee et al., 2006). 4D progress simulation could be overlaid on time-lapsed photographs via AR, such augmented photographs with 4D AR (AR contents show future work overlay on 3D objects in real world) simulation could compare discrepancies between the as-planned model and the as-built model in a consistent platform. However, the comparison was static and could not give real-time response. (Golparvar-Fard et al., 2009). In addition, augmented reality combined with 4D BIM could be used for automated operation-level construction progress monitoring, where onsite workers take daily photos and built 4D AR model which can detect materials to infer the actual state of progress. Nevertheless, this method needs taking many photos to build 3D point cloud model (Kevin et al., 2014). Further, a framework for cloud-based augmented reality using real time information for construction progress monitoring was proposed, which creates an automated real-time bidirectional flow between construction site and planning office, but it still need passive data acquisition at the first step (Soman et al., 2017).

1.3 Limitations in Previous Research

Previous researches by using BIM method or AR method do improve construction progress monitoring and schedule control, but they tend to get the as-built data from construction site as first step and then compared with as-designed 4D BIM. Thus, management team members only find discrepancy after it happened. Such lagging method cannot be used for finding potential problems and conducting real time construction site monitoring. In addition, construction workers still have to spend long time on data acquisition like photo taking or spend high cost for laser scanning device. There is a totally different situation for modular construction. Modular construction, in which all units are produced in manufacturing factory then assembled on construction site in a planned sequence, and have shorter schedule than onsite construction in similar volume. Moreover, any wrong assembly will definitely cause schedule delay and extra cost for rework. So real-time progress monitoring system avoiding wrong assembly before error happens is required by modular construction.

In order to improve modular construction progress monitoring and solve problems mentioned above, this study aims to develop a prototype by integrating real time AR and 4D BIM. To achieve our research goal, we focus on three questions: how to link 4D BIM with construction site directly via AR content, how to check modular components assembled in correct position and unit, and how to ensure modular components assembled in right sequence and date. In following text, workflow of this system and AR registration method will be introduced at first. Next we demonstrate what functions this system has and how it works step by step for progress monitoring. Finally we give discussion and conclusion about our system.

2 Method

2.1 Workflow

The as-designed 4D BIM data of modular components contains: 1) 3D information such as shape, size and floor; 2) 4D information like sequence and date. Firstly all the 4D BIM information related to construction progress monitoring is imported into this real-time 4D AR system via screen display, 3D BIM information is transferred into such AR registration part, which refers to the alignment of spatial properties (Schmalstieg et al., 2016). Meanwhile 4D BIM information is be restored into AR database for progress monitoring. Afterwards target position at as-built construction site will be located according to AR registration method, so construction management team is able to use displayed 4D AR content to compare as-built status in real world. The workflow of the 4D AR progress monitoring system for modular construction is shown in Figure 1.

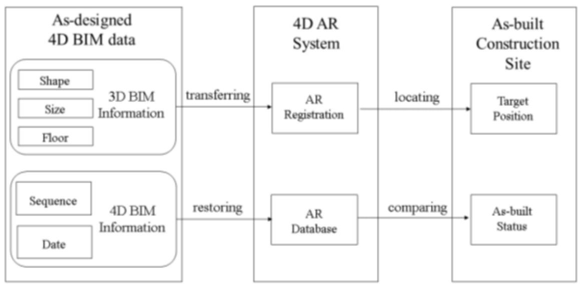


Figure 1. Workflow of 4D AR construction progress monitoring system

2.2 AR Registration Method

Fiducial makers are usually used for AR representation, however there are many limitations of marker-based AR on construction site, e.g. AR representation is easily failed by partial occlusion (João et al., 2018). Compared to marker-based AR, markerless AR method, in which any part of the real environment can be tracked in order to place virtual objects, is suggested for construction engineering (João et al., 2018). Even markerless AR methods can support construction process, currently major types of common markerless AR representation rely on features recognition (Teichrieb et al., 2007). As progress goes on, features for AR registration are always changed because site scenes keep changing, which means common markerless AR methods cannot show AR content seamlessly and there are still limitations for AR uses on construction sites. In those cases construction progress monitoring is still hysteretic and unexpected loss may still exist.

To give real time monitoring, construction site, 4D BIM and AR content should be linked with each other. In the described concept we use another markerless AR registration method related to relative coordinate system between objects and camera. There are two concepts in BIM model: 1) Project Base Point, which defines the origin (0, 0, 0) of the project coordinate system and becomes reference point for measurements across the site; and 2) Survey Point, which identifies a real-world location near the model and defines the origin of the survey coordinate system to provide a real-world context for the model. We coincide Project Base Point and Survey Point in a same origin and build up the World Coordinate System which is related to real-world objects, then every point of a modular unit gets its own coordinate. If there is a real fixed monocular camera facing to objects in real world, then every point of this camera will also get its own coordinate. Such fixed camera could be put on crane mast, which is helpful to determine its position and simulate in BIM model. We make this real camera into a simplified computation model named Pinhole Camera Model in computer vision area and choose camera's optical center as origin to build a new coordinate system, which is called Camera Space in computer vision area. Because there is no object deformation between the two coordinate systems, we can transfer every unit's coordinate in World Coordinate System to Camera Space by rigid transformation. Through this method, AR content representation is registered by relative coordinate to camera space instead of any marker or feature, so that AR content can be linked with real construction site directly. Even there are people, machines or scaffolding in the camera image, AR content will not be affected. Fig.2 shows relationship between these two coordinate systems, a rotation matrix R and an offset vector $\vec{T}$ makes object transfer coordinate systems, and AR content of objects was shown by Camera Space.

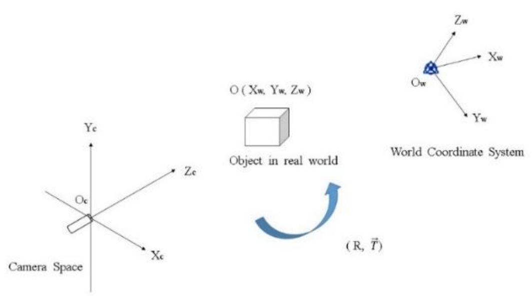


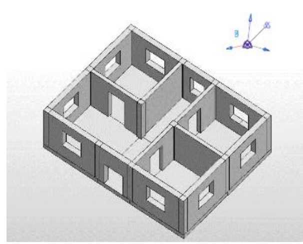
Figure 2. Relationship between world coordinate system to camera space

The equation for coordinate system transformation is shown in Eq.1. (X_c, Y_c, Z_c) means object's coordinates in Camera Space, (X_w, Y_w, Z_w) means object's coordinate in World Coordinate System. R means rotation matrix and $\vec{T}$ means offset vector. By using this transformation method, there is no change of objects' shape and size, objects shown in screen will reflect actual views in real world.

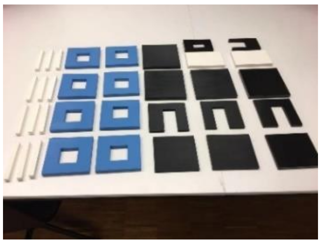
$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \\ 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{R} & \boldsymbol{T} \\ 0^T & 1 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix} \quad (1)$$

3 System Development

To verify the method mentioned above, we developed a prototype system. This progress monitoring system, developed for construction project management team, represents AR content at beginning and use as-designed AR content to compare with as-built site status in real time. The system developed 3 function modules: 1) 4D Date Module, this module restores date information of 4D BIM, users can choose and see finished work and planned work in different dates through AR; 2) 3D BIM Module, in this module 3D BIM information like shape, size, etc. is transferred into AR content, we use 3D AR overlay as target position which is ensured by such AR registration method, then modular units will be moved and matched with AR overlay; and 3) 4D Sequence Module, in this module we release 4D assembly sequence via 4D AR animation, it gives both progress monitoring and navigation to construction area. In next part we will express details about how to use these function modules step by step. BIM software Revit and game engine Unity3D is used for AR prototype system development. A modular BIM model and mock up components are used for demonstration, shown in Figure 3.



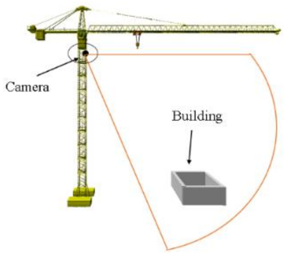
(1) BIM model with World Coordinate System



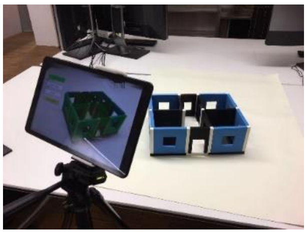
(2) Mock up components

Figure 3. BIM model and mock up model

To simulate real construction situation, we used a tripod as crane mast and an Android pad as fixed camera and monitoring screen. Such prototype is shown in Figure 4.



(1) Fixed camera on crane mast



(2) Simulation by tripod and Android pad

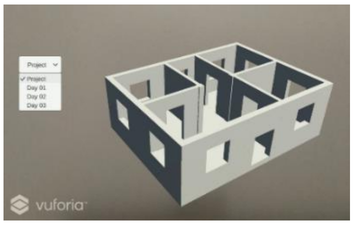
Figure 4. Prototype of this AR system

4 Case Study Based on a Mock Up

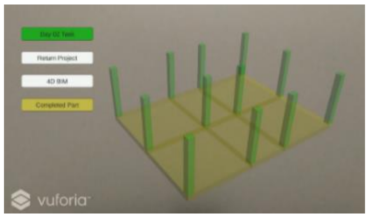
To show how this prototype works, we use a case study based on a mock up here. The mock up, consists of several components like floorslabs, walls and columns in one floor, is used as a modular construction project. Then we use an Android pad fixed on a tripod to simulate camera on crane. This system works on assembly process, users just need fix the camera and click some AR buttons. By using this system, users can check whether every unit is assembled in right position, sequence and date. There are three main steps to use it: (1) Date Selection; (2) Real Objects Match; and (3) 4D AR Animation. In following text we will give details about how to use our system step by step.

4.1 Step 1: Date Selection

The first step is choosing date in 4D Date Module. After starting our system, users can choose date to represent AR content of date information via a dropdown menu. On such AR user interface, *Project Button* in initial scene shows the final construction project status and different construction dates. Day Task scene (*Day 01*, *Day 02*, *Day 03 Buttons*) shows finished work in previous days via yellow overlay and intraday work via green overlay. Click *Return Project Button* will leave current date scene and come back to initial project scene, which helps users check AR data between different dates. In the presented case, initial start scene shows the completed status of modular BIM model in white opacity, Day 02 scene includes finished floorslabs in yellow overlay and planned columns in green overlay, shown in Figure 5.



(1) Project button and day task button

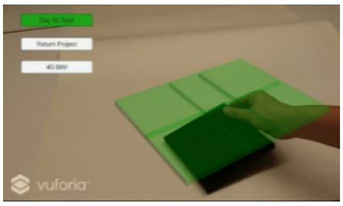


(2) Day 02 task scene

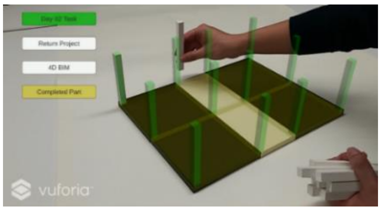
Figure 5. Different buttons and scenes

4.2 Step 2: Real Objects Match

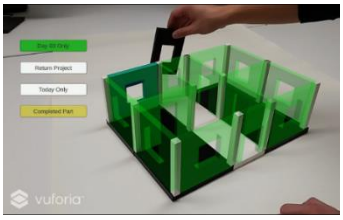
Second step is to match real objects with green AR overlay. AR content is represented before components' match. There are 4 match scenarios in our system: 1) Match before construction, this scenario presents works of first day, in which there is only green overlay in this scenario because no component is assembled before construction; 2) Match with finished work and planned work, in this scenario finished work has been matched with yellow overlay, planned work will be matched with green overlay; 3) Match with intraday work, this scenario only shows intraday work via green overlay, which can give intuitive combination between real objects and planned work; 4) Match with completed project, in this scenario all the components have been assembled, green overlay is still existed because last modular component is moved to match with green overlay. Every match scenario is related to 3D BIM Module. If a real modular component matches with green overlay perfectly in shape and size, such unit is assembled in right position. By this function, users can check whether a real modular unit is put on right position while it is close to assembly point. Besides if a real unit is deviated or missed from corresponding AR overlay, a construction error happened and users can adjust construction plan immediately. Different match scenarios are displayed in Figure 6.



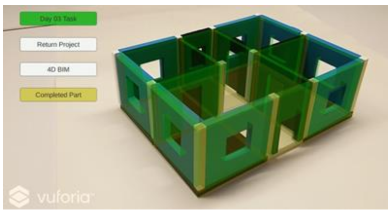
(1) Match before construction



(2) Match with finished work and planned work



(3) Match with intraday work

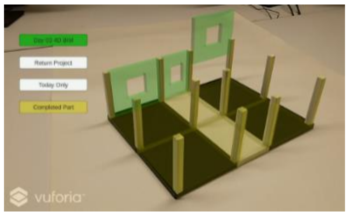


(4) Match with completed project

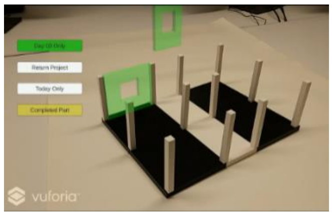
Figure 6. As-built objects match with as-designed AR content

4.3 Step 3: 4D AR Animation

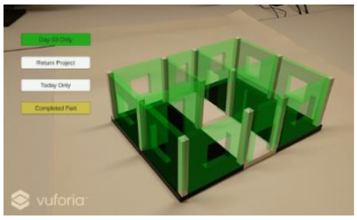
In order to give real-time monitoring and navigation of intraday work, the last step to use our AR system is 4D AR animation. Another 4D BIM information, sequence, is also linked with real construction site directly through 4D Sequence Module, shown in Figure 7. *4D BIM Button* shows 4D live animation on its own date scene, in which previous work represented by yellow overlay is also displayed for comparison. Such animation shows assembly sequence extracted from construction schedule plan. By touching *Today Only Button*, AR monitoring system only represent 4D live animation on that date, which match with real world objects precisely and intuitively. Through this progress monitoring function, construction management team can check intraday assembly sequence conveniently. If a modular component follows assembly sequence in 4D AR animation, such unit is assembled in right sequence. By this function, users can check whether a modular unit is assembled in correct sequence while it is close to assembly point.



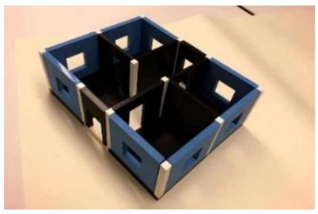
(1) BIM 4D animation with finished work



(2) Today Only animation



(3) Final 4D match



(4) Assembled modular components

Figure 7. 4D assembly sequence monitoring

5 Discussion and Conclusion

This paper proposed a real time 4D AR system for modular construction progress monitoring. Also we introduced workflow of this system, AR registration method this system used, what function modules it has and how this system works step by step. By using a markerless AR registration method represented by relative coordinate and a fixed monocular camera, BIM 3D data like shape, size and floor can be linked with construction site directly. Objects in real world match precisely with AR content. Additionally 4D BIM information such as date and sequence can be restored in AR database and released as live animation, which can give helpful support to progress monitoring and work schedule check. This AR system, targeting at nature of modular construction, can help construction management team avoid potential schedule problems before construction work start. Besides this system make it easier for users to check whether every component is assembled in correct position and sequence. Construction management team will have better construction schedule control and decision making through our AR system, which can both save money and time for a modular construction project. In the future work, we will have a further development of real-time communication function between construction management team and crane operator to avoid wrong assembly of modular components.

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