A Construction Progress On-site Monitoring and Presentation System Based on The Integration of Augmented Reality and BIM

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Abstract –

An on-site construction progress monitoring and presentation system is herein developed that overlays the virtual building information model (BIM) onto the real-time scene of the construction site using augmented reality (AR). The system utilizes the novel AR technology of simultaneous localization and mapping (SLAM), which is a real-time positioning technology based on visual-inertial odometry and point cloud map construction. Based on the scanned 3D environment point cloud and the adopted plane detection method, the indoor positioning is first initialized by attaching a virtual BIM component, which is set up on the centerline for alignment, to the corresponding real component at the actual site environment. Then, according to the completion surface of the actual object, the parameters of the position offset are kept adjusted at different construction stages, so the model can remain in position with the current scene. In this manner, the 3D BIM will be superimposed and displayed on the real-time view of the site based on the device's understanding of the environment through the recorded point cloud map using SLAM. In addition, the system also provides application modules for monitoring the project progress on-site. The on-site engineer can perform data collection through the designed system by interacting with virtual objects, with visual feedback provided for monitoring progress and evaluating project performance. To monitor the progress of a construction project on-site in real time, a method is proposed to quickly update the SLAM-based indoor positioning for adapting to a changeable construction environment. This compensates for the lack of visualization in the current construction management methods.

Keywords –

Augmented reality; Simultaneous localization and mapping; BIM; Construction progress management

1 Introduction

Augmented reality (AR) has many applications in the field of civil engineering, where the aim is to calculate the user's orientation and position to superimpose virtual objects and information onto the real world through a display device, thereby providing the user with the corresponding 3D model information and spatial details of the project site. The augmented reality positioning mode differs according to the location and use, in addition to variations in the resulting usage restrictions.

In the life cycle of construction projects, as building information modeling (BIM) is gradually maturing and being promoted, the combination of AR and BIM can be used to display increasing amounts of building information. Through visualization technology, the use of traditional 2D drawings has been traded for a more intuitive 3D model, and by combining the model with the actual scene to aid in decision-making, the design, materials, and configuration can be checked whether they are congruent with the designer's concept. If there are issues with the construction, immediate modifications can be made, thereby greatly reducing the errors during design, and reducing the cost and time of retrofitting after construction completion. While some previous studies have attempted to apply AR to the field of architectural engineering [1-3], the applications have been mostly limited to outdoor construction sites or existing construction sites.

Furthermore, in the project life cycle, the construction stage is where most changes occur and is the stage most prone to errors, with immediate corrections being challenging. Once the procedures have errors, the domino effect caused by errors will cause significant delays and cost increases. Therefore, the accuracy of message transmission of relevant construction operations, flow processes, and information between various construction units appears to be particularly important. A closer look at the construction on-site environment can reveal several characteristics such as a “harsh environment”, “many on-site stacking objects and construction equipment”, “huge and rapid changing construction environment”, “difficulty in equipment setup, update, and maintenance” and “uncertainty in environment situation”. As a result, the positioning of an AR system on a construction on-site becomes a major challenge. For many of the technologies used in augmented reality such as GPS, marker indoor positioning, Bluetooth, Wi-Fi, and RFID, the use of some external sensor devices to initialize the AR system is required. Additionally, apart from inadequacies in efficiency and accuracy as well as a higher cost, for the rapid vicissitude of the construction environment, there is a need to set up a device such as a Bluetooth device for positioning, along with installation difficulties and the time-consuming and complex maintenance and updating. In traditional construction management, for progress tracking and checking the construction tasks, there is a need to manually collect data, illustrations, and other information from all construction units, which, can be a quite time-consuming and labor-intensive operation. Presentations through text and data do not provide adequate visualization for the on-site personnel. There is not enough specific intuition. It is not easy to immediately present the work tasks in progress within the local space, and for professionals from different backgrounds, further errors may result in message uploading[4]. Even with the assistance of 3D simulation in BIM, the construction personnel still have to rely on their spatial reasoning and map out the illustrations or 3D models to the physical space, and thus, real-time discussions cannot be made timely on-site, thereby further affecting the time and cost. Meža [5] used AR for the visualization of the preliminary design and the monitoring of the construction on-site, and when compared with other applications, AR was found to effectively and drastically improve the intelligibility of information.

This study attempts to apply an existing AR framework and propose a set of construction management systems based on AR and BIM that are suitable for the construction stage. Through the visual tracking of simultaneous localization and mapping (SLAM) and AR system initialization based on dynamic reference benchmarks in response to the rapid changes and uncertainties of the construction environment, when the construction environment changes drastically, the BIM model is quickly fitted and positioned to improve the updating efficiency. In combination with construction management, interaction with the BIM model is conducted through AR for comparing the pre-planned construction progress with the actual progress on-site as reported by on-site personnel, as well as providing assistance in checking construction tasks. As compared with traditional construction management, visualization technology can be used to enable on-site personnel to view progress more intuitively and accurately, and to look for possible problems or risks in advance.

2 Objective

A “construction progress integrated management system based on augmented reality technology” is herein created with the aim to integrate the ARKit augmented reality framework as developed by Apple Inc., BIM, and construction management concepts, and present them on the site at the construction stage. Apart from the electronic construction management data collection and incorporating progress calculation functions into the system framework, this study proposes a model positioning and fitting system framework that is suitable for an indoor construction site through existing AR tools. The target application is under construction project sites.

For the model positioning and fitting operation flow process, first, due to the unpredictable on-site environment and the characteristics of environmental changes at the construction stage, the on-site configuration cannot be accurately predicted and no fixed object can be used as a positioning reference point. Thus, the pre-setting of a reference point is challenging and it is necessary to set a dynamic reference plane when positioning the BIM model, whereby the plane is used as the basis for initializing the model positioning. This reference plane can be dynamically determined according to the instantaneous configuration of the on-site environment and the offset position can be measured using the setting position in the original model. Then, the visual-inertial odometry (VIO) technology in ARKit is used to perform the positioning and feature point mapping of the AR system initialization in an uncertain space environment, and to create fitting-assisted reference components through existing structures or objects on-site during the mapping process. In this process, the reference components are used as fitting corrections for the 3D model when drifting is generated when a device is moved. Finally, the plane detection technology is used to pre-set the corresponding position of the initial dynamic reference plane in the BIM model onto the actual site. By entering the position parameters in advance, the AR system initialization is completed as the 3D model is fitted onto a relative spatial position. The operation preprocessing flow process for the initialization is shown in Figure 1. Through this process, quick dynamic positioning and fitting of the model can be achieved. Subsequently, the model repositioning and fitting can be carried out according to the recorded feature point maps in response to the changing construction environment, thereby improving the efficiency of system initialization and achieving a marker-less indoor positioning. The actual operating process is shown in Figure 2.

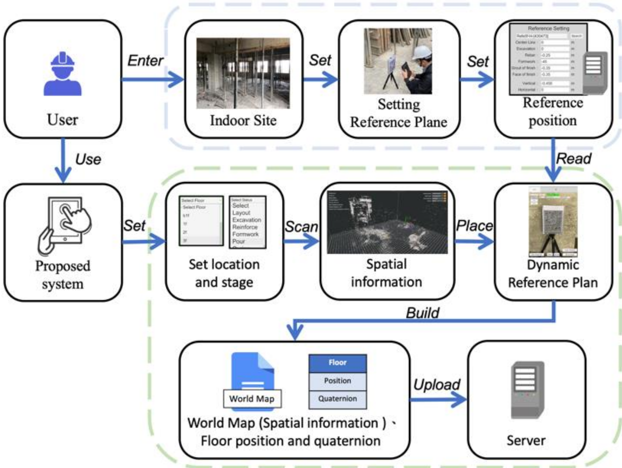

Figure 1. The pre-setting process of the proposed system.

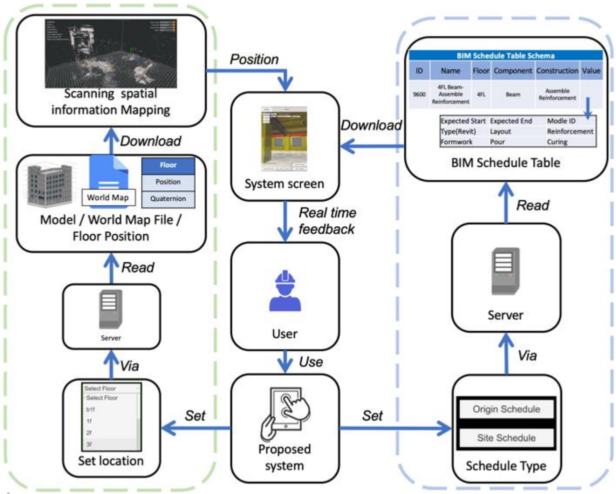

Figure 2. The operating process of the proposed system.

Finally, the BIM model and the construction schedule are integrated to achieve a mechanism for automatic collection of construction task data, daily management operations, information transfer, progress information visualization, and feedback. The mechanism further improves the project AR management framework that is lacking in relevant literature for traditional construction management.

The construction progress integration management system using AR will take the construction of a reinforced concrete (RC) as an example. Main construction operation tasks are divided into lofting, steel bar binding, formwork assembly, grouting, and concrete curing. To verify the proposed system, the positioning is subjected to a verification test on an actual site to monitor whether the BIM models can be efficiently fit to the site and are not affected by the work surface at various construction stages, and whether the system positioning accuracy is sufficient to meet the site requirements. Moreover, through the system display and comparison with the traditional construction management methodology, the proposed system is demonstrated to integrate planning and actual site information, and display this data on an AR device. The progress summary information is displayed using different colors corresponding to construction status, and it is verified that the user can perform queries and comparisons on construction task progress with the use of virtual reality as well as efficiently check construction tasks.

3 System Requirements and Mechanisms

To achieve these objectives, the functional requirements of the system are investigated, with Unity3D and ARKit frameworks used as the system development platforms. These analysis functions include the AR indoor positioning process based on SLAM visual inertia, system pre-position operation test, reference plane design and deployment rules, preprocessing of the BIM model, and the BIM model component information and progress information storage framework. The following subsections focus on introducing the functional analysis and proposed system methodology.

3.1 BIM model preprocessing

To achieve the "construction progress integration management system based on augmented reality technology" as mentioned in the aim of this study, the proposed system needs to establish a BIM model using 2D illustrations. Analyzing the project scale, characteristics, management organization, management method, and work breakdown structure diagram of the RC structure, the scope when operating the system will provide visual feedback to users based on the floor level. To reduce the burdens on the display and storage space of the device, the pre-position processing of the BIM model segments the 3D model into floors, and stores them on the server for users to download. The primary pre-setting process is shown in Figure 3.

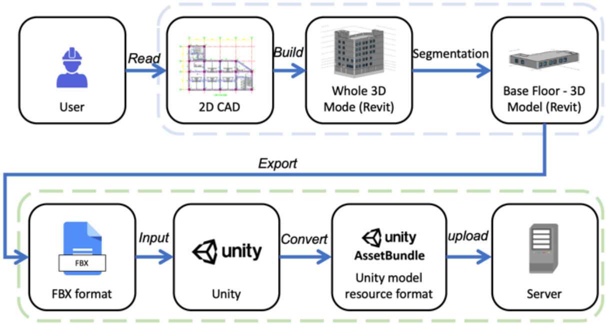

Figure 3. Pre-setting process of the BIM model.

3.2 Augmented reality indoor positioning

The ARKit framework is used as a development tool in iOS. ARKit is a framework based on SLAM combined with an inertial measurement unit (IMU). SLAM refers to a camera device equipped with a lens determining its own position and stance (sensors) by repeatedly observing environmental feature points (e.g., ground surface, walls, columns, etc.) during a movement process, starting from an unknown location in an unknown environment, and then calculating the feature point coordinate data intercepted from the image by its own position and stance to construct the feature point map, thereby achieving the self-positioning and mapping.

3.2.1 ARKit framework

SLAM has mostly resolved the two problems of positioning and mapping. "Positioning" refers to the device location as self-estimated in its environment at that moment, while "mapping" (a.k.a. feature points or a point cloud map) refers to the model of the identified local environment, i.e. the environmental map with incremental feature points as found through continuous movement and repeated observation of environmental features using positioning. The visual SLAM processing procedure is divided into five steps: (1) camera information image sequence acquisition and access, (2) visual-inertial odometry (VIO), (3) calculation optimization of device position and stance, (4) closed-loop detection of repeated observations, and (5) feature point mapping. In the ARKit, stance estimation of the IMU has been added into the second step of SLAM to measure the acceleration and angular velocity of the device, and through Kalman filtering the most accurate position of the device is obtained. Through a combination of the camera and inertial sensor, the estimation errors are lowered to increase the positioning accuracy. In the framework of ARKit, feature points captured by each image will be stored as anchors attributes, indicating that there is an anchor list for tracked positions or objects as detected on the map., If images that are being taken are repeatedly identified, the device location can be repositioned.

3.2.2 Plane detection

As mentioned above, many feature points can be extracted from the camera images to develop a tracking and positioning feature point map. Under this framework, these feature points not only can be used for estimating the device position, any three extracted points can form a plane, and then these triangular planes is subjected to processing through an algorithm and several plane optimizations. Finally, a sufficient number of planes can be used to estimate the real physical plane. Through the estimated plane, model components can be placed at the captured anchor position through interaction with the AR system.

3.2.3 Analysis of feature point mapping

Based on the abovementioned positioning theory of SLAM under the ARKit framework, an analysis is conducted on the construction and operation behavior of the feature point mapping, and the results of a test of using the device movement rate for positioning and mapping, as well as using the measurement mode on the construction site, are presented as shown in Figure 4 and Figure 5.

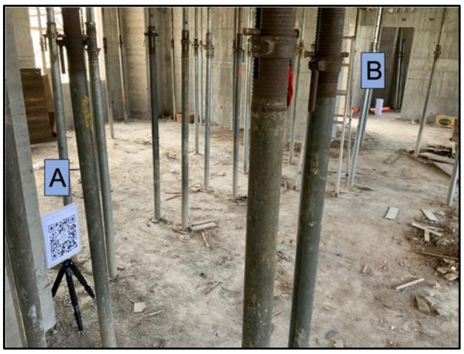

Figure 4. Actual environment.

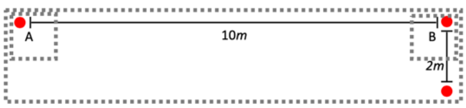

Figure 5. Schematic top-view.

From multiple test results, the movement rate and 3D error with a varying number of intercepted feature points was obtained (Figure 6). Under the same movement range, it can be found that there are more feature points intercepted at a slower movement rate, and the accuracy in positioning and mapping is also relatively higher. For the variance in errors with the number of feature points found via interception corresponding to the fitted model, it can be found that the errors generated at movement rates less than 0.5 m/s gradually converge to approximately 1% of the overall movement distance. Therefore, when the camera intercepts the feature points, blurring will increase in the camera due to the high-speed movement, which will cause errors in positioning and mapping. At slow movement speeds (approximately 0.5 m/s), the generated errors begin to converge, and the resulting error falls to around 1% of the movement distance. Errors in a very harsh environment can almost be on the order of inches [6].

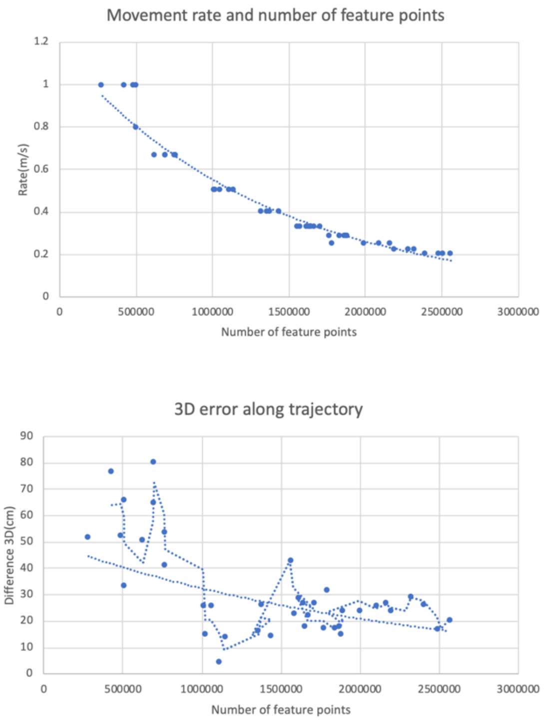

Figure 6. Movement (top) and 3D error (bottom) with number of feature points.

3.3 BIM model fitting mechanism

The model fitting mechanism is mainly to align one of the BIM model components with the corresponding real object for placement, and then to use the relative relationship between a single component of the BIM model and the entire model to fit the entire model on the map of feature points, thereby superimposing the model on the site. However, due to the unpredictable construction environment and characteristics such as environmental changes at the construction stage, the on-site configuration cannot be predicted and no fixed objects on the site can be used as positioning reference points for the feature point map. Therefore, a dynamic reference plane is required as a reference point for position initialization. This reference plane can be dynamically configured according to the configuration of the site environment at the time of initialization. When configuring the reference plane, the positional distance difference $\Delta\boldsymbol{R}$ from the reference plane in the BIM model is measured via centering and leveling operations, as shown in Figure 7. Finally, the offset data is recorded in the database. When fitting the model, the model file is first downloaded from the server according to the selected plane position and stage. Then, the system will first read the coordinate $\boldsymbol{P}$ and angle $\boldsymbol{Q}$ of the previously loaded model. Next, the selected virtual reference plane is aligned and placed on the actual reference plane; during the placement, angles $\boldsymbol{P}'$ and $\boldsymbol{Q}'$ (see Equation (1)) are obtained. Finally, the angle rotations of $\Delta\boldsymbol{Q}$ (see Equation (2)) and the model position movement distance of ΔP for the reference plane offset of $\Delta\boldsymbol{R}$ will be first calculated and then uploaded together to the server as the basis for the model fitting (see Equation (3)).

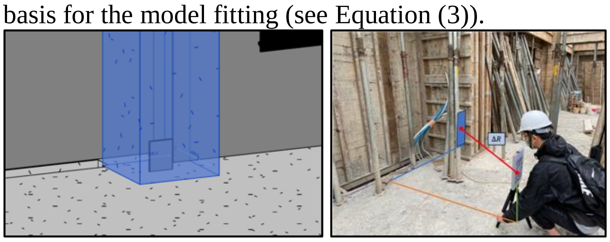

Figure 7. BIM model reference (left) and actual environment (right).

$$Q'[x' \quad y' \quad z' \quad w'] = \Delta Q \times Q[x \quad y \quad z \quad w] \quad (1)$$

$$\Delta Q = Q \times Q'^{-1} \quad (2)$$

$$\Delta P = |P - P'| + \Delta R \quad (3)$$

3.4 Integrating BIM model data and progress schedule data

During the construction project, due to the influence of different factors, each in progress construction task can either be ahead of schedule, behind schedule, or on schedule, further affecting the start of relevant subsequent tasks. As a result, the actual construction operations will change from the initial construction plan. Essentially, construction management and control are based on contracts that use the project schedule as a foundation, while for the proposed system, the user continuously updates the actual progress of work tasks on the BIM model via the AR system, as the BIM model components in the system framework are associated with their corresponding work tasks. Given that a user continuously interacts with the model to enter the actual construction progress to dynamically update the schedule, this dynamic update is based on the successive relationship of construction operation tasks. The overall schedule obtained is thus a real-time prediction of the overall construction length based on actual project progress. Estimations for subsequent tasks can be based on this dynamic scheduling and in the same manner, engineering performance evaluations can be implemented based on planning and actual on-site scheduling; early deployment and improvement can be made on subsequent implementation of the same standard layer using AR feedback for the actual situations that have happened on the site. The operating mechanism of the real-time dynamic update for the construction schedule is shown in Figure 8.

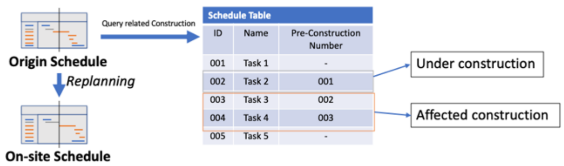

Figure 8. Operating mechanism of the real-time dynamic update for the construction schedule.

4 Application Scenarios

Based on the prototype system developed, four types of application modes that meet the practical requirements are proposed for integrating the virtual and real environments: (1) interface conflict and positional views, (2) component data presentation and task checklist, (3) construction progress presentation and progress comparison, and (4) presentation of affected construction tasks and construction simulation. These modes are applicable for the construction life cycle and acceptance and review stages, with the mode adjustable depending on the degree of detail in the BIM model and operation requirements. It is not necessary that one type of mode can only support operation in one stage. Below is a detailed display and description of these four modes following the characteristic classification of system operations.

4.1 Interface conflict and positional views

The first application mode is used for presentation before the construction of the structure begins. Surrounding a construction site, there are mostly existing buildings or structures such as adjacent houses, slopes, roads, and other structures. The aim of this application mode is to alleviate the ecological impact from the project site and to investigate countermeasures by viewing possible affected location (e.g. surrounding adjacent houses, slopes, channels, and other existing structures) before the construction starts, as well as confirming the construction disturbance range (e.g. construction access roads, earthwork, and material stacking areas, etc.) to determine the project configuration and for moving line planning. For the case study introduced in the present study, it can be clearly seen that there are slopes and existing channels surrounding the future water collecting well, as shown in Figure 9. Through the repetitive detection of the AR, the relative height of the water collecting well with actual possible affected location can be more clearly seen to discover problems in advance. The evaluation via repetitive detections determines whether the original design or construction plan needs to be further adjusted. During construction, this application mode can assist in confirming whether the depth after excavation is sufficient, as shown in Figure 10, and at the construction stage for the structure, this application can also assist in confirming the location of completed components on the site, as shown in Figure 11 for reference.

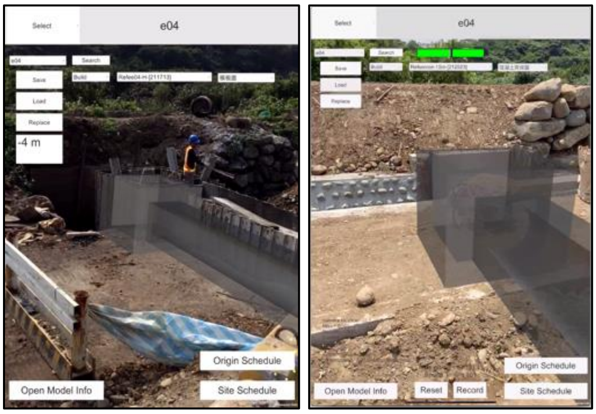

Figure 9. The elevation of the water collecting well and possible a location.

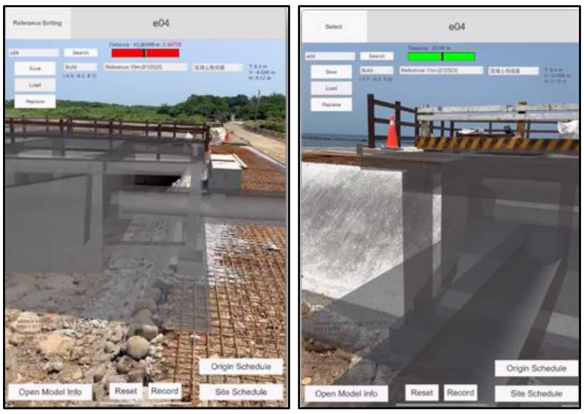

Figure 10. Excavation depth confirmation on the construction site.

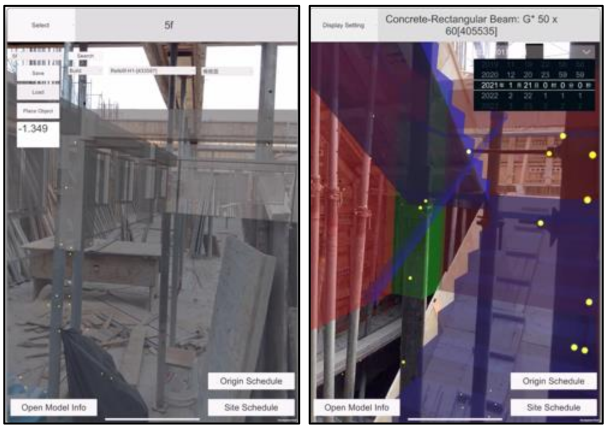

Figure 11. Indoor location assistance for the RC structure construction.

4.2 Component data presentation and checking form

The second mode is to tap and interact with the model after it is superimposed to present relevant information for the selected component. Apart from the attribute parameters and associated construction progress item information, the main presentation content also can have various attached documents according to the component type or usage requirements. Due to the association between components and progress, a user can therefore mark the completion of a system component directly as a unit for a construction task and be provided the construction progress. The information on the progress of components that can be provided to the user based on the ARKit real-time positioning when the system is operating at the construction stage is given below. The application procedure as follows:

1. When a project enters the construction stage, the user enters the location where a task is to be completed and then checks the task when completed to ensure the quality of project work.
2. The user moves toward the component to be checked after the completion of system positioning.
3. Attributes and progress information for the component can be obtained by tapping the component on the device screen.
4. When the quality audit confirms that there are no errors, the task for that component will be marked as complete and updated. At this point of time, following the date of checking, the progress for that will be determined as either ahead, on , or behind schedule. The system will update the dynamic progress schedule for subsequent associated work tasks according to the date of checking, so that the user can estimate future progress, as shown in Figure 12.

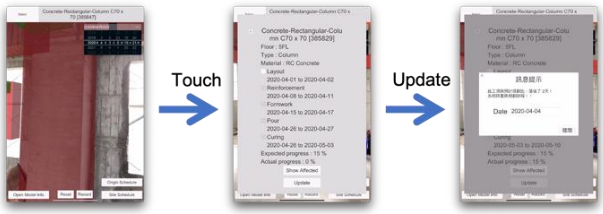

Figure 12. Component information query and task checklist.

4.3 Construction progress presentation and progress comparison

The third mode is to superimpose the actual objects with the virtual objects and view the current construction progress overview based on the schedule, where yellow, green, and red indicate in progress, complete, and delayed, respectively, as shown in Figure 13 (left). Moreover, this mode compares progress with the planning schedule and the actual checking date. It presents whether each work task in the past is ahead of schedule (green), on (yellow), or behind schedule (red), as shown in Figure 13 (right). On site, a user can carry out the presentation and review whether there are conflicts on the moving lines and configurations to adjust the schedule and for early deployment of subsequent work tasks.

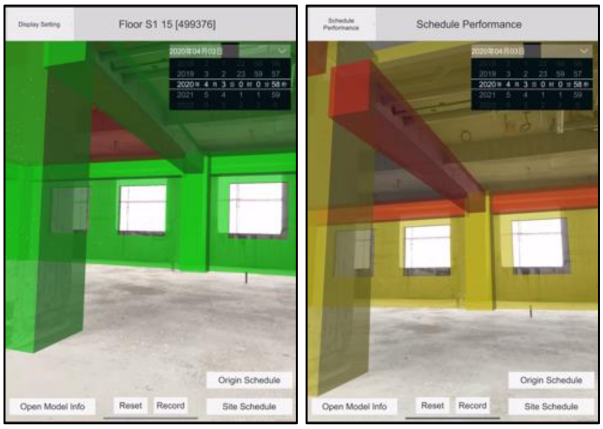

Figure 13. On-site progress presentation (left) and comparison of progress (right).

4.4 Presentation of affected construction tasks and construction simulation

The fourth mode considers the sequence of planned work processes and uses blue as the color for the work task component to be implemented in the future, so that the user can perform construction simulations on site, as shown in Figure 14 (left). Furthermore, following the results of using the previous several modes in sequence, for the components that are likely to be subsequently affected due to delays in the work process, the components are presented in orange, as shown in Figure 14 (right), giving the user a visual reference beyond than numerical data and text.

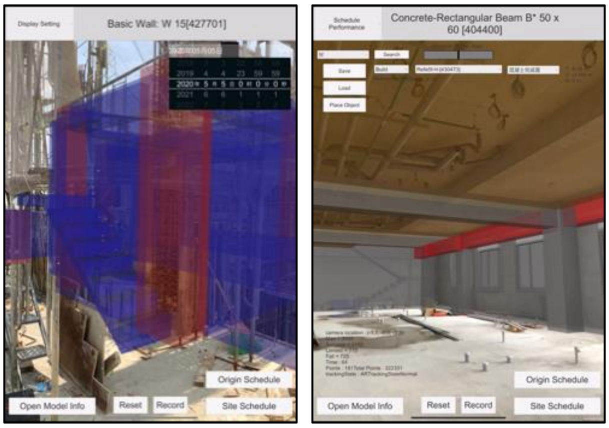

Figure 14. A construction simulation (left) and an affected work task (right).

5 Conclusions

This study proposed the “A Construction Progress On-site Monitoring and Presentation System Based on the Integration of Augmented Reality and BIM”. The aim was to carry out the positioning of an AR system at a construction site through the ARKit framework based on SLAM for an indoor site at the construction stage, and be able to respond to unknown and rapid changes in the harsh site environment. Under different construction stages, the dynamic reference plane without pre-setting additional sensor devices conducts rapid system positioning initialization. The indoor position is located by visually scanning the site environment characteristics, and then, by downloading the BIM-related information and progress information from the database, a virtual and real integration mode on site allows for viewing the elevation, position, and progress of components. Furthermore, data collection is conducted through user interaction with the AR system, and the collected data is integrated to provide visualized feedback functions, such as a comparison on the difference between planning and on-site actual progress and construction simulations. Adaptability, immediacy, synchronization, and convenience as provided by the proposed system can improve the efficiency of on-site construction personnel in understanding the progress, in planning, and in decision-making. Through the combination of AR and indoor positioning, the proposed BIM information on-site visualization can improve the existing BIM visual model, and can effectively and quickly collect and acquire information, thereby reducing complicated operations and the required time. Through the real-time visual feedback on site, the virtual and actual scenes can be superimposed on a single screen simultaneously, therefore supporting on-site construction monitoring and discussion. The future development of the system will be further integrated with computer vision for automatically identifying the completion rates of all BIM overlaid components in a scene through deep learning based AI.

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