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# On-site Visual Construction Management System Based on the Integration of SLAM-based AR and BIM on a Handheld Device

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## ABSTRACT

Recently, Simultaneous Localization and Mapping (SLAM) has been integrated into the development of AR systems. Using conventional SLAM adoption method to overlay a building information model (BIM) onto the image of a real scene on handheld device in a construction site will result in poor model overlaying accuracy owing to the relatively unique environment and monotonous texture of such environment. This paper proposes an adoption method of SLAM suitable for construction environment to improve positioning accuracy for the fitting of BIMs for the AR presentation. In addition, a AR system to visualize construction progress on-site is developed. It allows site personnel to input on-site work progress through an AR device, then compares the originally planned construction progress with the actual on-site progress, and presents BIM components using different colors in the AR mode to show whether work progress on each component is ahead or behind schedule intuitively.

## 1. Introduction

As building information modeling (BIM) technology matures, it continues to be extended to the planning, design, contracting, construction, operation, and maintenance stages of the life cycle of a building project (Eastman et al., 2009; Bansal, 2011; Becerik-Gerber et al., 2012; Irizarry et al., 2013; Park and Kim, 2013; Liu and Issa, 2016; Lu et al., 2020; Benjamin et al., 2022). With the improvement in performance of hardware and software, the use of augmented reality (AR) has also developed on various mobile devices. AR allows users to superimpose virtual models or objects on an image of the real world in real time (Azuma, 1997; Behzadan and Kamat, 2007; Viyanon et al., 2017; Chen et al., 2020; Zhang et al., 2021).

Traditional management software such as Primavera P6 Enterprise Project Portfolio Management (Oracle, 2023a) and Project (Microsoft, 2023a) offers professional scheduling management features, whether utilizing the Earned Value Method (Zhang and Zhang, 2023), Gantt charts (Lee et al., 2022), or Key Performance Indicators (Suqrat et al., 2017) to inspect construction progress. However, in the realm of communication during the construction process, paper-based or basic information devices are still in use, leading to a potential communication gap with on-site workers. Correspondence between management information (operational tasks) and on-site construction tasks can result in judgment errors.

Advanced commercial systems such as BIM 360 Plan (Autodesk, 2023), Aconex Construction Management (Oracle, 2023b), and Vico Office (Trimble, 2023) can utilize a 4D construction simulation based on the BIM model to compare the plan and actual progress. The utilization of BIM models in such systems allows for clearer conveyance of management information to on-site workers.

Integrating the principles of construction and planning management into an augmented reality (AR) application during the construction phase has the potential to improve communication, reporting, and discussion amongst on-site personnel. This approach allows for easy access to progress management documents, while also providing real-time information in the AR environment, allowing for timely and informed decision-making (Meza et al., 2015; Kim et al., 2018).

By utilizing handheld mobile device technologies such as ARKit (Apple, 2023) and ARCore (Google, 2023), as well as intelligent headsets such as HoloLens (Microsoft, 2023b), AR technology can be used to integrate 3D models, management

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information, and document usage into the real world, providing users with an immersive experience, as demonstrated by Connect AR (Trimble, 2022), Construction Augmented Reality (Argyle, 2021), Augmented Reality for Construction (Visual Live, 2021). During the construction phase, the construction environment undergoes frequent changes. Factors such as structural variations due to different stages of construction, the relative monotony of surface textures in the site environment leading to challenges in acquiring distinctive features, and discrepancies in scanning rates during equipment movement can result in model alignment deviations when operating AR devices. Consequently, recalibration and positioning become necessary. In the past, many studies have continuously explored the positioning technology required for model alignment, which will affect the quality of the model alignment in the real world.

When GPS is used indoors, the accuracy of satellite signals is greatly reduced because the of coverage. Thus, most GPS systems can only be used for positioning-related applications in outdoor spaces and cannot be used as effective positioning tools in indoor spaces (Muthalif et al., 2022). In order to implement positioning-related applications indoors, a variety of indoor positioning systems (IPS) have been developed. Commonly seen indoor wireless positioning technologies include GPS-based, radio-frequency identification devices (RFID), cellular-based, ultra-wideband (UWB), Wi-Fi, Bluetooth, ZigBee, visible light, acoustic signals, ultrasound (Liu et al., 2007; Gu et al., 2009; Wang et al., 2023). Studies have proposed that when users move about indoors, RFID, WiFi, Bluetooth, and the other positioning methods can be used to register the user's location, but the accuracy is susceptible to the environment, other interference factors, and device configuration. Therefore, apart from reducing external interference, a marker-based method can also be adopted to accomplish a more accurate model fitting (Feng and Kamat, 2012; Lee et al., 2017; Won et al., 2020).

Simultaneous localization and mapping (SLAM) technology (Durrant-Whyte and Bailey, 2006; Maksim and Ilya, 2018; Huang et al., 2023) has been applied to robots, autonomous driving, and other fields. SLAM has also been integrated into the development of AR systems. Development began with the demonstration and estimation of spatial data uncertainty by Smith and Cheeseman (1986), Smith et al. (1988). Real-time localization and mapping uses robots or mobile devices equipped with sensors and cameras. Starting in an unknown environment and location, during movement, the robot or mobile device repeatedly observes environmental features with its sensors and cameras, performs calculations, and uses them to determine its own positions and pose. Then, mapping with incremental environmental feature points is carried out based on its own positions and feature points captured by the camera. Real-time localization and incremental mapping can be achieved through the movement of the device through the environment. Subsequently, researchers have proposed different algorithmic methods to further optimize and solve the technological problems of positioning in SLAM (Dissanayake et al., 2001; Guivant and Nebot, 2001; Montemerlo et al., 2002; Xu et al., 2019; Xu et al., 2020; Kayhani et al., 2022).

With the growth in computational capacity of handheld devices, they are becoming more and more suitable for the application of visual tracking technology, so SLAM-based technology running on mobile phones can carry out localization with a map of feature points generated from a number of full frames in real time for positioning (Klein and Murray, 2009; Marino et al., 2022).

In summary, the main issues and limitations encountered when using AR technology for progress management during the construction phase include:

1. The construction site undergoes continuous changes during the construction process, leading to alignment deviations when scanning discontinuous surfaces.
2. The results of alignment during on-site scanning are also affected by the scanning speed rate.
3. Presenting progress management information through BIM models lacks intuitive means for construction managers, often resulting in communication issues and construction errors.
4. In order to obtain relevant information by selecting aligned models, the quality of model alignment becomes crucial as it directly affects the accuracy of information presentation regarding the comparison between the planned schedule and actual progress.

The author has initiated a research project to integrate augmented reality (AR), Building Information Modeling (BIM), and progress management on handheld devices during the construction phase. This study proposes an operational workflow for conducting progress management through AR systems, aiming to provide a solution for the aforementioned issues and limitations faced by on-site managers and construction personnel.

The study begins by addressing the common challenges related to information transmission and cognitive aspects among team members during the construction phase in Section 2. It further explores the difficulties encountered and improvement objectives when utilizing augmented reality technology in the construction site.

In Section 3, a compilation of previous research on the use of AR throughout the building lifecycle and the proposed system positioning methods are presented to determine suitable positioning techniques for the construction phase.

The Section 4 involves testing the application of AR technology during the construction phase, examining various issues and proposing corresponding solutions. The Section 5 outlines the preprocessing operations and system framework employed in this research, while the Section 6 explains the on-site alignment mechanism and the presentation method for visualized progress comparison.

The seventh section focuses on the implementation of the system at a construction site to validate its feasibility. Finally, a conclusion is drawn regarding the proposed implementation procedure in this research, highlighting both the limitations and advantages of the provided solutions.

## 2. Motivation and Objectives

Traditional management of the construction stage involves manually integrating the collected information and then presenting it through text, data, and illustrations in order to comprehend the progress, but its degree of visualization is insufficient, and it is not specific and intuitive. Even if BIM is used for simulation and assistance, on-site engineers still need to rely on their understanding of the space and the information obtained is mapped onto a real-space scene (Golparvar-Fard et al., 2009; Kwon et al., 2014). This research hopes to further integrate AR and progress management mechanisms to aid on-site engineers and managers to obtain progress information more easily, and to improve their ability to comprehend the construction progress.

However, in the life cycle of a project, the environmental changes in the construction stage are more complicated than those in other phases (Xu et al., 2020; Kayhani et al., 2022). Taking the construction of reinforced-concrete (RC) building structures as an example, stages such as layout, excavation, rebar tying, formwork assembly, concrete pouring, maintenance, mold removal, and renovation are carried out in sequence. Based on the different construction requirements of each part of the project, the temporary construction configurations required are different from the actual completed surface positions. Further examination of the construction site can reveal several characteristics, such as poor environmental conditions for setting up auxiliary positioning devices, various changes in environmental conditions with uncertainties, rapid changes in the construction environment, difficulty in updating and maintaining equipment after mounting, and temporary storage for many items and construction equipment. As a result, for those who need to adopt auxiliary equipment for positioning, when positioning is to be carried out at the construction site, the aforementioned problems must be overcome.

Taking into account the limitations of equipment setup conditions in a construction environment, this research makes use of the advantages of SLAM positioning (Maksim and Ilya, 2018), such as being usable in unknown environments with complex textures, no need of mounting positioning sensors, real-time operation, and easy updating, to overcome the problems of positioning on an indoor construction site, thereby improving the efficiency of use. Moreover, in an operational indoor construction environment, feature identification is used to locate the user's position in the space and the plane detection function based on the identification of feature points can be used to accomplish accurate model placement and fitting, and the corresponding building information can be viewed during movement.

To integrate SLAM-based AR with BIM models on handheld devices, the system needs to be able to locate the position and direction of the handheld device in space by combining the results of sensors with the scanning and matching of feature points. It also needs to take a plane based on a certain component identified through the feature points as the benchmark for model placement, so as to achieve the integrated VR presentation of a BIM model over the real building image, and then implement applications in this AR mode. However, in practice, during the construction stage of a building's life cycle, owing to the relatively unique environment and relatively monotonous textures of construction site, using existing feature-point positioning and model placement methods on the site will cause SLAM positioning to be susceptible to factors like scanning movement rate, map break points generated by path discontinuities when scanning feature points, and uneven model placement benchmarks, resulting in poorer model fitting accuracy. Therefore, this project focuses on the characteristics of a construction environment inside a building. This research proposes a SLAM application suitable for the AR presentation of a construction site, so as to improve positioning accuracy for the fitting of BIM models in an indoor construction site.

Furthermore, this research combines a 4D progress management mode, allowing site personnel to import on-site work progress by selecting the BIM model components through an AR device, then compare the originally planned work progress with the actual on-site progress, and use different colors on the BIM model presented in the AR mode to show whether the work progress on each component is ahead or behind schedule. The visualization allows on-site personnel to more intuitively and precisely control progress (Baek et al., 2019; Julia et al., 2019; Ricardo and Cesar, 2020).

Thus, the aim of this research is to create an on-site visual construction management system based on the ARKit AR system development platform on iOS handheld devices and its built-in SLAM positioning technology. SLAM is suitable for use in an AR presentation to effectively fit BIM models on a construction site and the 4D progress management mode compares actual progress on-site with the construction schedule in an AR mode for superimposition of BIM models on a construction site image. It implements a visual system for performing activities like recording project progress, daily activity management, and progress information feedback. It has specific and intuitive VR integration to improve the efficiency of on-site construction progress management activity.

## 3. Related Research

The application of augmented reality (AR) in engineering has been increasingly proposed, encompassing aspects of design, construction, and facilities in the construction life cycle. With the evolution of technology, there have been changes in the positioning techniques.

To accommodate various application scenarios and environmental constraints, different positioning technologies are utilized to reduce the deviation between model fitting and the actual environment. These technologies include photogrammetry, global positioning systems, and wireless positioning, as well as marker-based or markerless methods.

In the research compiles and investigates various positioning techniques, highlighting their limitations when applied in the construction phase. Subsequently, the research selects Simultaneous Localization and Mapping (SLAM) as the positioning technology, aiming to further explore its limitations and potential improvements.

During the construction phase, the traditional management model faces the challenge of analyzing complex progress control data to identify actual or potential delays. It becomes difficult for on-site construction personnel to figure out the extent of the affected areas. Golparvar-Fard et al. (2009) proposed using captured daily outdoor progress photos to create 4D models. Using computer visualization techniques to superimpose the models, augmented reality (AR) was achieved. The study expressed that to implement progress tracking for indoor components, a sufficient number of photos of the paths from outdoors to indoors is required. These limitations arise from the variations in weather conditions, which impact the lighting conditions and camera to capture images accurately. The changes in lighting can affect the quality and alignment of the projected augmented reality elements with the real environment, leading to potential difficulties in achieving accurate overlays.

Augmented reality (AR) could bridge the gap between the digital and physical realms. Meža et al. (2014) proposed methods to leverage GPS positioning in outdoor environments and establish an AR system for mobile devices. The researchers investigated three progress monitoring methods: Gantt charts, simulations, and AR. They demonstrated that AR has the ability to reduce cognitive load and optimize the monitoring process. However, the study also highlighted three major challenges. Firstly, the limited hardware capacity of mobile devices posed a constraint on the implementation of the AR system. Secondly, visual obstructions in the environment could hinder the effectiveness of AR overlays. Lastly, when using GPS positioning technology indoors, signal interference caused by obstacles could significantly impact the accuracy of positioning.

Overall, the study identified the potential benefits of AR in progress monitoring but acknowledged the need to address hardware limitations, visual obstructions, and positioning accuracy challenges for optimal implementation of the technology.

When the device moves continuously, it will affect the positioning accuracy. Li et al. (2018) adopts a differential positioning method to precisely determine the user's location, subsequently utilizing SLAM technology to track the rendered object and improve the visual quality. This method enabled stable and dynamic tracking of pipelines, even in markerless and outdoor environments. Compared with existing techniques, their method can improve the spatial accuracy of pipeline rendering.

If AR technology is to be applied to indoor construction sites, then there is a need to further explore the use of indoor positioning technology. Cheng et al. (2017) used AR for interior renovation and discussed marker-based and markerless positioning modes. They considered that the software development kit (SDK) used for marker quality and AR has a considerable influence on the accuracy of marker-based positioning. The markerless mode is suitable for mobile devices and adopts a more precise positioning method.

The utilization of wireless positioning techniques (including RFID, WiFi, and Bluetooth) achieved indoor positioning while users are in motion. The accuracy of positioning is unavoidably susceptible to environmental conditions, external interferences, and equipment configurations. Moreover, challenges arise in maintaining wireless electronic devices due to factors such as wet installation conditions, unstable power supply, and rapid changes during the construction phase (Zafari et al., 2019).

Related studies on positioning using SLAM have also proposed combining it with VIO (Li and Mourikis, 2013; Leutenegger et al., 2015; Li et al., 2017; Tan et al., 2022). Adopt extended Kalman filter (EKF) to fuse visual odometer and accelerometer sensors to dynamically generate topological maps. They used mobile device orientation sensors for pose estimation, indoor positioning, and navigation. Through streamlined equipment, fairly good positioning accuracy can also be obtained (Gupta et al., 2016).

Due to the poorer environmental conditions during the construction stage, the setup of positioning systems or marker-based facilities at this stage often results in damage due to variations in the construction environment and construction impacts, thereby affecting the establishment of related facilities. The existing literature on SLAM technology has paid limited attention to addressing the issue of accumulated scanning errors resulting from continuous movement in construction site environments. These alignment errors between virtual and real objects have a significant impact on the user's ability to effectively utilize construction management interfaces.

This research adopts the dynamic reference plane method as a relative reference positioning benchmark for use indoors, combined with SLAM for indoor positioning, to improve the use of various indoor positioning technologies in the construction stage. It also proposes a set of recommended procedures to achieve good model positioning accuracy. Additionally, it builds an AR development and function integration platform on mobile devices through

**Table 1.** Summary of Works in the Application of AR in Building's Life Cycle

| | Meža et al., 2014 | Li et al., 2018 | Baek et al., 2019 | Wu et al., 2020 | Chen et al., 2020 | Zhang et al., 2021 | Bajpai and Amir-Mohammadian, 2021 | The proposed system |
|---|---|---|---|---|---|---|---|---|
| Application | Constr. Mgmt. | Facility Mgmt. | Facility Mgmt. | Constr. Mgmt. | Facility Mgmt. | Navi. | Navi. | Constr. Mgmt. |
| Stage in Life Cycle | Constr. | Operation | Operation | Constr. | Operation | Operation | Operation | Constr. |
| Indoor or Outdoor | Outdoor | Outdoor | Indoor | Indoor | Indoor | Indoor | Indoor | Indoor |
| Localization Technology | GPS | GPS+SLAM | Image-based (CNN) | SLAM | iBeacon (BLE) | SLAM | SLAM | SLAM |
| AR Platfrom | Android | Unity | HoloLens | Ubuntu | Xcode | Unity | Unity | Unity |

Unity 3D (Bajpai and Amir-Mohammadian, 2021; Hasan et al., 2021; Torresani et al., 2021), whereby AR technology can assist project managers to compare digital and real information to enhance the efficiency of on-site project management (Wu et al., 2020). Table 1 summarizes and compares the abovementioned works in the application of AR in a building's life cycle with the proposed system, thus highlighting their differences.

## 4. Proposed Method for Applying SLAM in an Indoor Construction Site

Through the exploration of AR technology in engineering applications and the analysis of positioning techniques and their limitations, this study has chosen to adopt SLAM technology as the positioning technique for the construction phase. Using the operational platform constructed with the ARKit framework, field tests were conducted utilizing SLAM positioning technology to achieve the goal of construction management using AR technology.

In order to understand the potential object alignment errors that may arise when adopting SLAM positioning technology in construction sites, which could affect construction management execution, this study was designed to perform practical system operations in a reinforced concrete construction site with a floor area of 280 square meters, spanning from B1F to 6F.

The on-site tests were divided into two stages. In the first stage, the standard SLAM positioning method was utilized, and the measured positioning errors were recorded and analyzed to initiate preliminary discussions. In the second stage, based on the obtained results, improvement strategies were developed and implemented for further validation. Finally, suggested activities workflow were proposed for applying SLAM in an indoor construction site.

### 4.1 Field Tests of SLAM Positioning Technology in an Indoor Construction Site

#### 4.1.1 Feature-Point Scanning and Path Test

At the beginning of this research, when implementing SLAM mapping on a construction site, the user followed an arbitrary path and searched for existing site objects such as columns, beams, and walls located along the path. This process involved scanning the existing building using the camera of a mobile device to create a map of feature points, as shown in Fig. 1.

During the scanning process in this mode, it was observed that due to the sequential nature of construction activities, there was often a lack of continuity between different structures within the construction site. For instance, during the rebar tying phase for columns, the walls and beams might not have been constructed yet, resulting in gaps or discontinuities in the scanning path. Consequently, the distance to scannable targets might be too far, or there may be no objects available for scanning, leading to a loss of image continuity. This hampers the estimation of equipment movement locations, impacting the mapping continuity, as shown in Fig. 2.

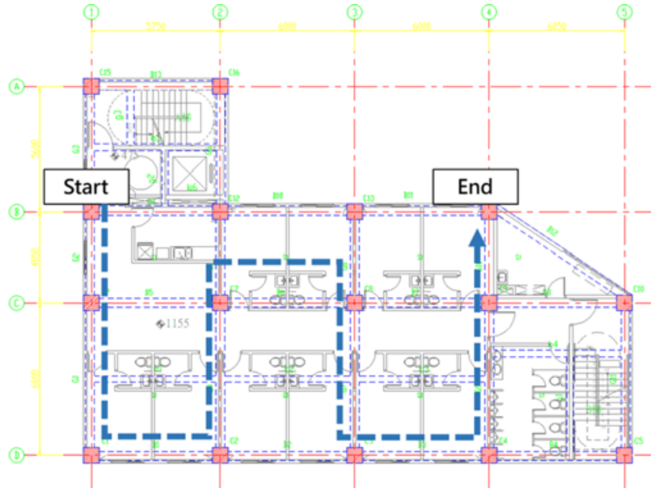


**Fig. 1.** Schematic Diagram of an Arbitrary Scanning Path

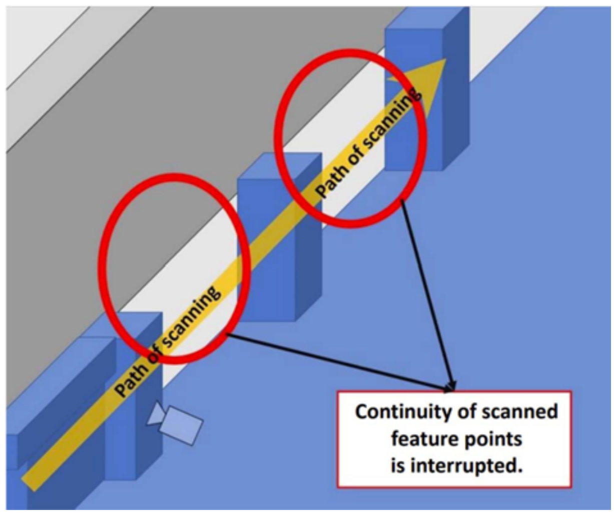


**Fig. 2.** Error in Estimation of Device Position due to Interruption in the Continuity of Feature Points

Currently, in order to effectively extract feature points, it is necessary to move the camera over a significant distance at various intervals to search for suitable targets. However, this movement can cause image blurring due to excessive camera motion, resulting in offset errors between the estimated position based on visual calculations and the extracted feature point coordinates. As a result, the accuracy and coverage of the mapping process are reduced.

Furthermore, in arbitrary scanning environments without path planning, it becomes challenging for users to identify previously positioned scenes for accurate positioning and model fitting.

#### 4.1.2 Test of Movement Rate During Feature Point Scanning

During the process of scanning feature points using mobile devices, this study discovered that rapid camera movements resulted in the inability to maintain focus, leading to blurred images and disrupting the continuity of the image sequence. Consequently, errors in estimating equipment locations during positioning occurred, thereby impacting the accuracy of mapping. Additionally, the number of extracted feature points varied at different average movement rates, which further affected the visually calculated position estimation.

#### 4.1.3 BIM Model Placement and Fitting Test at an Indoor Construction Site

By utilizing the ARKit framework based on SLAM technology, the environment plane can be recognized based on the device's camera. This enables the placement of models at specified locations based on the identified planes. However, during the construction phase, various environmental interfaces are commonly encountered, such as layout, rebar tying, formwork assembly, and concrete pouring. These interfaces often exhibit discrepancies with the actual completed surfaces. Achieving precise positioning using fixed planes or points becomes challenging in the construction site environment.

Furthermore, the planes presented in the construction site may not align perfectly horizontally or vertically due to the ongoing construction activities. Consequently, the planes recognized by the device exhibit angular errors compared to the design surfaces. This angular deviation introduces subsequent angular discrepancies during model fitting. The magnitude of this deviation becomes more pronounced as the distance between the model and the positioning point increases.

#### 4.1.4 Testing the Influence of Site Environment Changes on Mapping

SLAM technology relies on environmental recognition to accurately position and fit models. However, in some situations, the existing feature-point map becomes outdated and cannot align the BIM model correctly with the site. Factors such as temporary material placement or installation of temporary facilities during different construction stages can lead to changes in the completed feature-point map. In such cases, it is necessary to rescan the environment to update the model's recognition and placement.

This Research observes that each scan's general feature-point map is influent by various construction activities, including:

1. Placement of construction equipment and machinery.
2. Stacking of materials during their delivery or removal.
3. Existence of project deadlines and potential rush work.
4. Varied efficiency of different work teams.
5. Interactions between different trades and their impacts.

These construction activities affect the accuracy and reliability of the feature-point map over time. Therefore, it is crucial to regularly update the feature-point map to account for changes in the construction environment and ensure accurate positioning and model fitting.

### 4.2 Method for Adopting SLAM Positioning Technology in an Indoor Construction Site

Summarizing the abovementioned test results, this research found that SLAM can be applied to indoor construction site positioning, but it is necessary to propose a set of recommendations for operational use according to the characteristics of the indoor construction environment. This research analyzed the test results and makes the following recommendations for positioning applications using SLAM in indoor construction environments, as shown in Fig. 3. The recommendations have indeed yielded significant improvements in test outcomes in indoor construction sites. Consequently, the alignment errors have been effectively reduced to an acceptable level, ensuring their suitability for

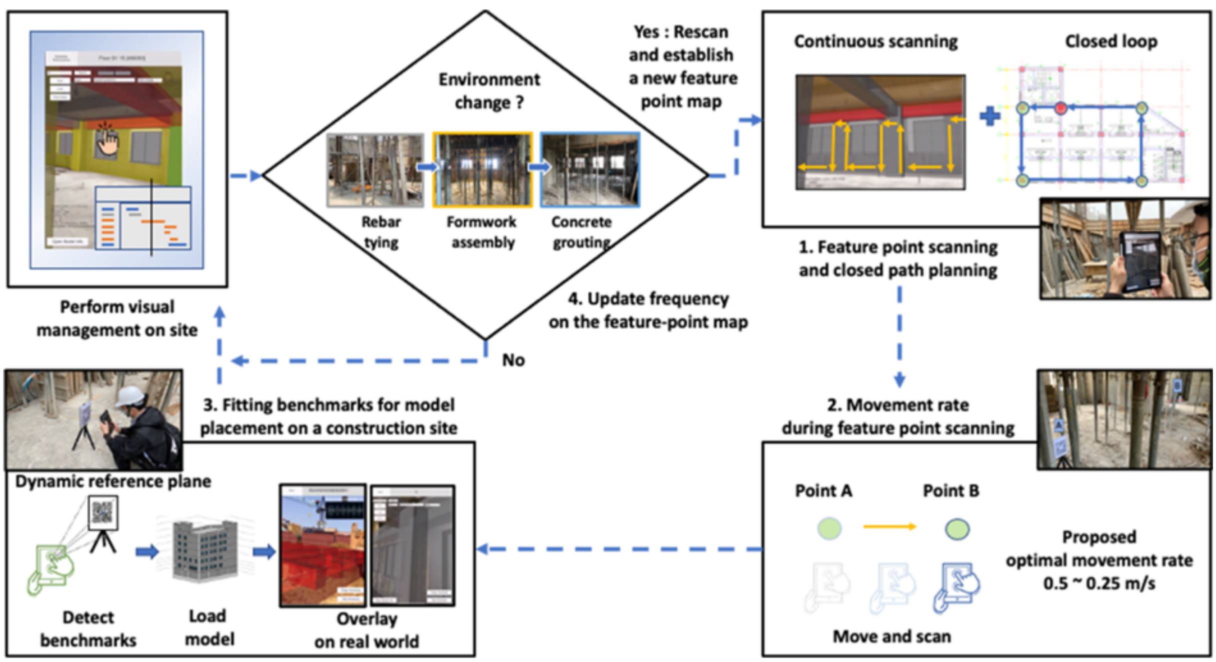


Fig. 3. Proposed Method for Applying SLAM in an Indoor Construction Site

construction management requirements.

### 4.2.1 Feature-Point Scanning and Closed Path Planning

Based on the positioning principles of SLAM, this research explores the causes of the aforementioned issues. Through analysis and extensive testing within an indoor construction site, it has been determined that the camera has a limited effective scanning distance. Capturing sufficient feature points from distant objects or scenes proves challenging, resulting in disruptions to the continuity of the image sequence. Consequently, errors accumulate during mapping and trajectory estimation, leading to compromised accuracy in location estimation.

Furthermore, maintaining image continuity during scanning operations, detecting closures through repeated observations, and avoiding image blur caused by excessive camera movements all impact the accuracy of the feature-point map construction.

Based on experimental measurements and analysis, it has been discovered that maintaining continuity among ground feature points facilitates improved camera scanning continuity and reduces the need for large-scale movements of the handheld device during mapping, as shown in Fig. 4. Consequently, this approach effectively minimizes error generation. It is also critical to plan reference objects at the starting and ending points, as well as the turning points, of movement paths prior to execution. These reference objects serve as anchor points for equipment position recalibration, enhance system efficiency during operation, and mitigate instances where feature points for equipment repositioning cannot be found due to drift.

Thus, the recommendations for scanning path planning for indoor construction sites are as follows:

1. Taking the loop closed path as the basis for planning the path of a feature-point map, the key objects must be included within the route. The ground-surface link between various scanned objects is used for continuous scanning to establish the continuity of feature points used in the position estimation. Finally, the user returns to the starting point for error correction of closure detection.
2. When scanning existing objects, it is recommended to include objects at the points of four corners of the activity range, where the objects can act as an offset calibration reference, as shown in Fig. 5. The offset calibration reference is good for re-fitting when the image drifts. It is also possible to set up multiple offset calibration reference objects according to the key points of viewing, in order to increase the efficiency of correcting the positions of equipment during translation, and to take the abovementioned ground-surface feature scan as the feature-point link for various reference objects.

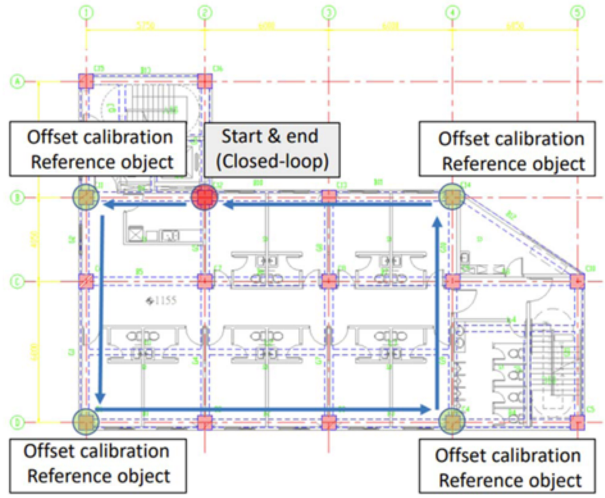


**Fig. 5.** Path Planning Recommendations for the Construction of Feature-Point Map

### 4.2.2 Movement Rate During Feature Point Scanning

The research conducted an analysis of equipment movement rates for positioning and mapping. A measurement test was set up on the construction site, as shown in Fig. 6. The analysis involved examining the number of extracted feature points and measuring the error between the positions of virtual and physical

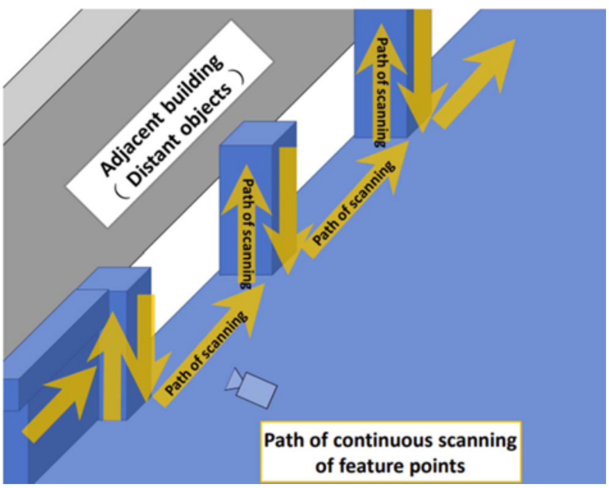


**Fig. 4.** The Usage of Ground Surfaces as Links to Maintain Continuity between Object Feature Points

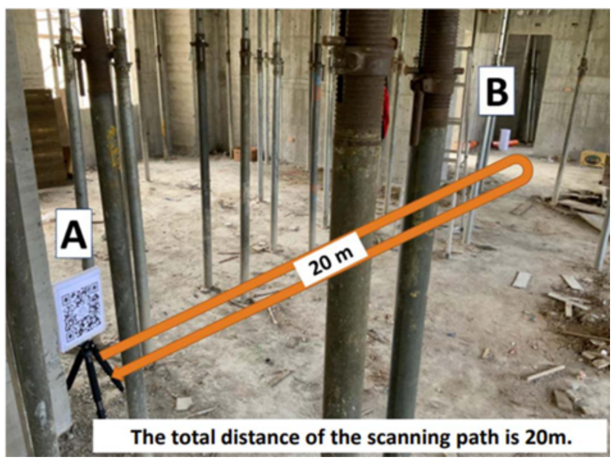


**Fig. 6.** Schematic Diagram of the Movement Rate Experiment and Test Path on the Real Scene

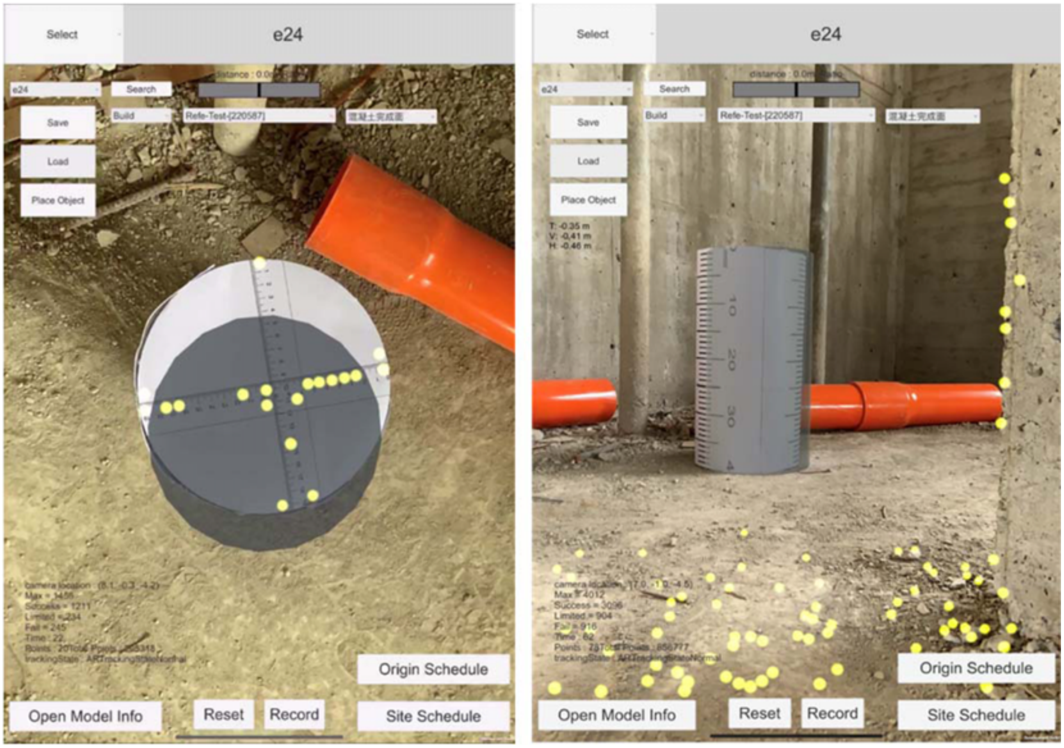


**Fig. 7.** AR Images of the Cylindrical Column in the Model Fitting Scenes of the Movement Rate Experiment

**Table 2.** Test Results of Offset Distances for Different Movement Rates

| Movement rates (m/s) | 1.00 | 0.67 | 0.50 | 0.40 | 0.33 | 0.29 | 0.25 | 0.22 |
|---|---|---|---|---|---|---|---|---|
| Quantity of feature points | 425,877 | 707,946 | 1,067,360 | 1,389,794 | 1,641,753 | 1,846,344 | 2,012,671 | 2,392,528 |
| Distance between center of virtual and physical objects (cm) | 7.9 | 7.6 | 5.2 | 4.4 | 4.9 | 4.3 | 5.2 | 4.8 |

objects based on the images captured after scene placement, all performed under different average movement rates and for the same movement range and scene.

The test procedure is as follows:

1. Take point A as the scanning starting point, set point B as a solid cylindrical object, and set up a virtual object at the same position in the virtual test scene.
2. In each test, moving at different average rates, begin scanning the environment from point A, and then return to point A through point B to perform closure detection of the feature-point map and calibrate the feature points.
3. Then, place the well-set virtual test scene from point A as the benchmark.
4. Through the identification of the environmental feature points at point B, determine the location of the user and fit the model. Subsequently, the position of the physical cylinder is determined through the images and the scale plane-detection function pre-marked on the physical cylinder, so as to calculate the error in the position of the virtual object at point B, as shown in Fig. 7. Next, the number of cumulative feature points are recorded for each image frame during the recording process.

The test results and errors for the virtual and physical objects at different movement rates are shown in Table 2. At the same movement range, a slower average movement rate yields more intercepted feature points, and the resulting errors in the virtual and real positions of the model are also small and stable. The results show rapid movement of the scanning action causes the camera to have poorer picture quality, resulting in an insufficient number of feature points being extracted and a map with poorer accuracy. When the average movement rate is slower than approximately 0.5 m/s, the mean distance error at the center position is under 5 cm, which demonstrates that the precision of the generated feature-point map is better and stable. Based on the test results, an optimal average movement rate of approximately 0.5 – 0.25 m/s can be obtained; the average number of feature points extracted ranges from 53,368 to 100,633 points/m.

In order to effectively let the user control the movement rate, this research provides a reminder function of the movement rate when scanning the feature points by quantifying how many feature points need to be accumulated within the movement distance. This function is based on calculating the distance between two images as $D_i$ (Eq. (1)). The real movement distance of the two images is calculated based on the superimposition of

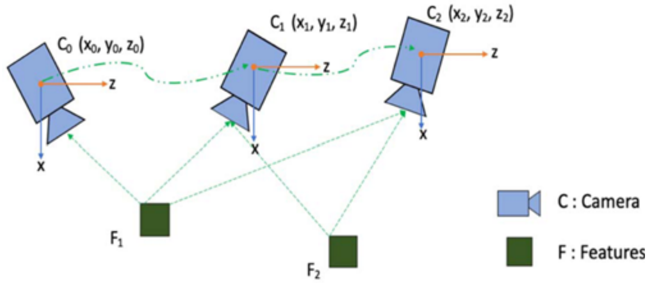


**Fig. 8.** Extraction of Feature Points Based on Repeated Observations to Estimate the Camera Position

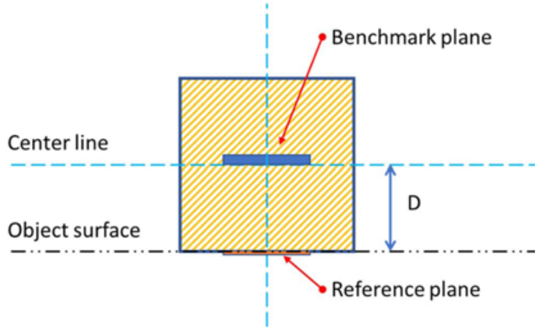


**Fig. 9.** Relational Diagram of the Benchmark Plane in the Model with the Reference Plane on the Completed Surface of a Column

multiple images, as shown in Fig. 8.

The average value of the previous test data is taken to be the number of feature points under a preset unit distance as $P_{\text{Unit}}$. Multiplying $P_{Unit}$ by the real distance of $D_R$ (Eq. (2)) yields the required number of feature points for the movement distance, defined as $P_{Expected}$ (Eq. (3)). Finally, compared with the real number of feature points obtained in each frame over an elapsed time, denoted as $P_{Scan}$, the ratio of real and expected real-time feature points can be obtained, denoted as $P_{Ratio}$ (Eq. (4)).

$$D_i = \sqrt{(x_{i+1} - x_i)^2 + (z_{i+1} - z_i)^2} \tag{1}$$

$$D_R = \sum_{i=0}^{n} Di\sqrt{(x_{i+1} - x_i)^2 + (z_{i+1} - z_i)^2} \tag{2}$$

$$P_{Expected} = D_R * P_{unit} \tag{3}$$

$$P_{Ratio} = \frac{P_{Scan}}{P_{Expected}} \tag{4}$$

If $P_{Ratio}$ is greater than 1, then the user has met the specified movement rate and the image will be displayed in green. If it is less than 1, then the rate is too fast and must be slowed down and the image will be displayed in red. At this point in time, the user needs to return to the position of the previous scene to re-calibrate the camera position to reduce the occurrence of errors.

### 4.2.3 Fitting Benchmarks for Model Placement on a Construction Site

In order to accurately determine the model position, this system adds a plane component into the BIM model as a benchmark, called the benchmark plane, as a basis for the placement and fitting of an entire model on the site. Through the benchmark plane method, this research attempts to place the model of an entire floor space. During model pre-processing, it is recommended to select a suitable column or the center line of a stable object for the placement position of the benchmark plane according to the construction direction and sequence on site, as a reference for the overall model placement.

Among the different environmental interfaces in the various construction stages, the aim is to take the basis of the benchmark plane on the center line with the completion surface of each stage as the reference plane, i.e., the surface of rebar, formwork, and concrete at the completion stage, and to measure its distance from the center line as the difference in position with the benchmark plane in the BIM model, as shown by D in Fig. 9, to obtain the real benchmark-plane position of the model. The benchmark of model placement can be adjusted according to on-site progress. Not needing to fix the placement at a specific location is beneficial to the measurement and calculation of the distance offset for subsequent model fitting. However, in this research, the abovementioned method was measured on site. If a surface of an on-site object is taken as the fitting benchmark for the model, then the reference plane will be unevenly placed, mostly because of the influence of the construction environment or state, resulting in an offset of oblique generated after model fitting.

In order to solve the problem of the oblique in model fitting, this research placed a benchmark plane for improvement, called the dynamic reference plane. With the aid of a device installed on the reference plane, the centering and leveling of the reference plane can be ensured, so that the placed model can accurately fit onto the real site.

Equipment for the dynamic reference plane includes:

1. Plane image: An image plane that provides easy extraction of feature points and a placement space of the same size as the plane in BIM, so as to provide accurate placement of the model.
2. Leveling device: This consists of two sets of pipes with bubbles, to assist in horizontal calibration during the mounting of a plane.
3. Adjustable tripod: This is used to assist in the leveling operation of a plane in response to a complex environment and terrain.

Throughout the model placement procedure, the system detects the dynamic reference plane by first applying the BIM model and fitting the benchmark plane on the center line of the object onto the dynamic reference plane, as shown in Fig. 10. Subsequently, it rotates the model by an angle of θ and moves it by distances of $d_x$, $d_y$, and $d_z$, as shown in Fig. 11. Then, placement of the model is completed.

### 4.2.4 Update Frequency on the Feature-Point Map

As the construction progresses, the environmental conditions undergo changes corresponding to different stages, such as

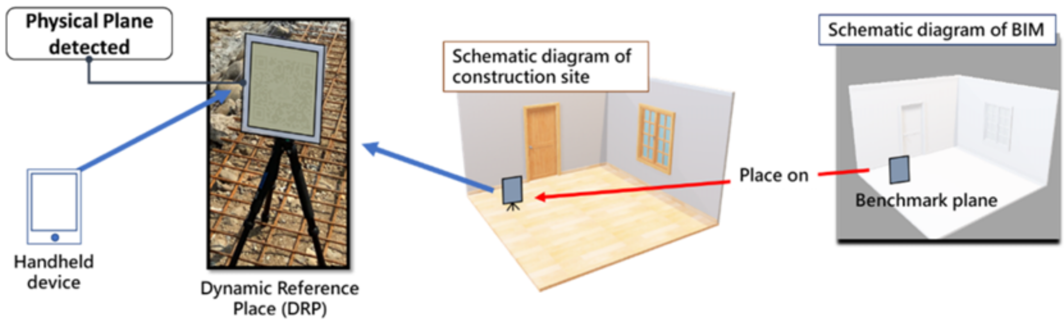


**Fig. 10.** Schematic Diagram of Installation of Dynamic Reference Plane on Site, Physical Plane Detection, and Overlay of Benchmark Plane in the Model on Dynamic Reference Plane

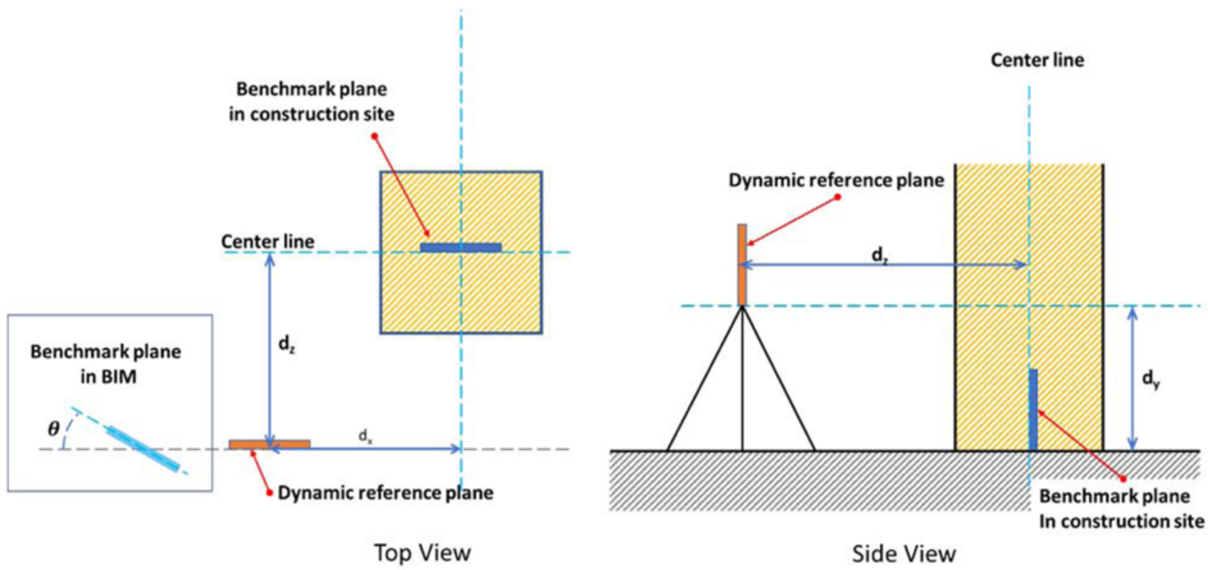


**Fig. 11.** Positional Relation Diagram of the Dynamic Reference Plane on Site with the Benchmark Plane in the Model

rebar assembly, formwork assembly, and grouting completion. Consequently, the previously scanned feature-point map of the environment becomes outdated and cannot be used for fitting the BIM model accurately. Therefore, it is crucial to conduct on-site tests to determine an appropriate update frequency for the feature-point map.

Through actual measurements and scanning of environmental changes, the feature-point map is repeatedly adjusted to match the site conditions. Since the feature-point map is based on the completion status of each construction stage and the evolving interface and material flow within the site, the time frame for reusing a previously created feature-point map for model fitting is typically limited to 1 to 3 working days. If this time limit is exceeded, the changes in the construction site environment render the previous feature-point map ineffective for equipment positioning and model fitting. In such cases, it becomes necessary to rescan the environment and establish a new feature-point map for the current construction stage.

## 5. System Framework

Based on visual inertial real-time positioning, SLAM model fitting, and augmented reality (AR) visualization of progress information, this study proposes a framework for an AR-based construction progress monitoring system. The framework comprises two distinct stages: system pre-processing and system operation.

### 5.1 System Pre-Processing Framework

During the pre-processing stage of the system, the data to be imported construction project's BIM model and the construction schedule for progress management. Additionally, in the operational phase of the system, users are provided with visual feedback on a per-floor basis. Hence, the BIM model needs to be pre-divided into floor-based fragments. The system's pre-processing stage can be delineated into three key steps, as outlined below, while referring to the procedure shown in Fig. 12.

1. Establishment of the BIM Model: To reduce the burden on device display and storage capacity, the complete model is segmented by floor during the pre-processing phase of the BIM model. These segmented models are stored on the server, allowing users to access and download them during the subsequent system operation stage, based on the construction progress. Initially, the BIM model is created using Revit,

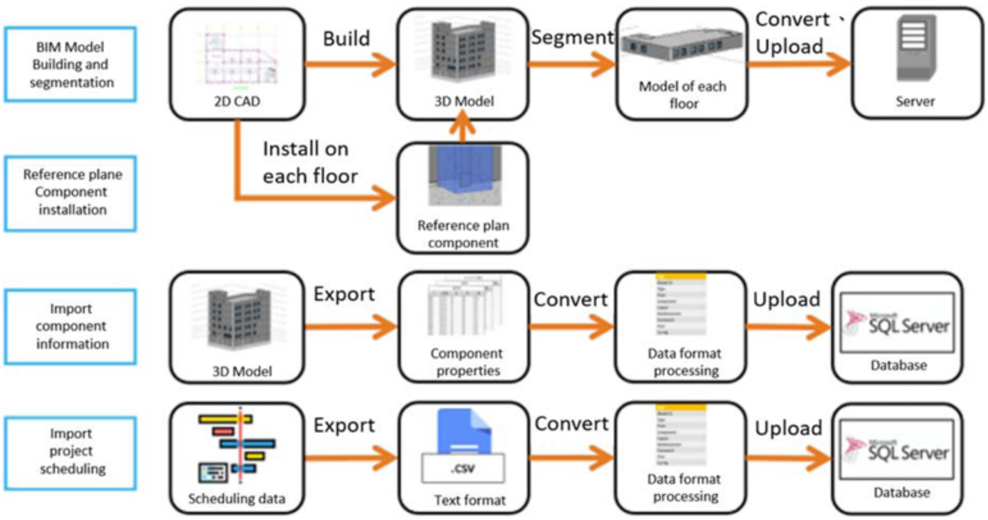


**Fig. 12.** System Pre-Processing Framework

after which it is fragmented by correlating each floor with its corresponding construction elements. The model is then exported in. FBX format, adhering to Unity's compatible reading format. Furthermore, the fragmented model is imported into Unity, converted into the Unity communication transmission format known as Unity AssetBundle, and subsequently uploaded to the system server. Consequently, users can conveniently download the relevant floor model pertaining to their location for seamless utilization within the AR system.

2. Importing component information: The system incorporates model component information derived from the BIM created with Revit and subsequently exported. This information encompasses various aspects of the model components, including columns, beams, walls, slabs, and other relevant details. Through the system's application mode, the data pertaining to these model components is exported in either Excel or text file format. Subsequently, the exported data is organized in a structured manner that aligns with the system's application logic, and it is stored within the database. When a user engages with the AR mode to view the model, the system performs queries on the database to retrieve the pertinent information associated with the selected model component.
3. Importing construction progress: To establish an AR system environment that seamlessly integrates 4D construction and planning management for effective progress control of construction projects, it is essential to compare the visually imported on-site work progress with the pre-determined planned progress. This necessitates the pre-planning of construction activity schedules using project management software. The resulting planned schedule is then exported into a .CSV file format, which is subsequently imported into the database of the AR system. This enables the system to conduct progress comparisons with subsequent imports during the system's operational stage, facilitating accurate monitoring and control of project advancement.

## 5.2 System Operation Framework

Before deploying this system in a new construction environment, it is imperative to conduct a feature point scan of the surroundings using a camera. This step is repeated each time the system is utilized. By identifying the environmental feature points, the user can determine the relative position of the BIM model within the actual scene. This positional information is then presented through the integration of VR technology.

Within the framework proposed by this research, the main operational workflow comprises three steps. The procedure is as shown in Fig. 13, as follows:

1. Placement and fitting of the model in the AR environment: The user must search for a suitable location to mount the dynamic reference plane based on the on-site configuration status. This will serve as the starting point for scanning the environmental feature points of the construction site while following the pre-planned path. To correct any errors generated during the scanning process, the system will perform closure detection based on the scanned scene. Once the image on the dynamic reference plane has been scanned, the system will detect the position of a physical plane by performing plane detection. The user will then use the model placement function to align the selected plane with the real position and place the plane components. The feature-point map data (.worldmap file format) and model placement information generated during this run will be uploaded to the system server for storage using the upload function.
2. Indoor construction site positioning mechanism: After the feature-point map is established and the BIM model is placed and fitted on it, the system will download the model, feature-point map, and model placement position information based on the user's location and the selected floor. By utilizing the feature-point map, the system can identify the environment, locate the user's equipment within that space,

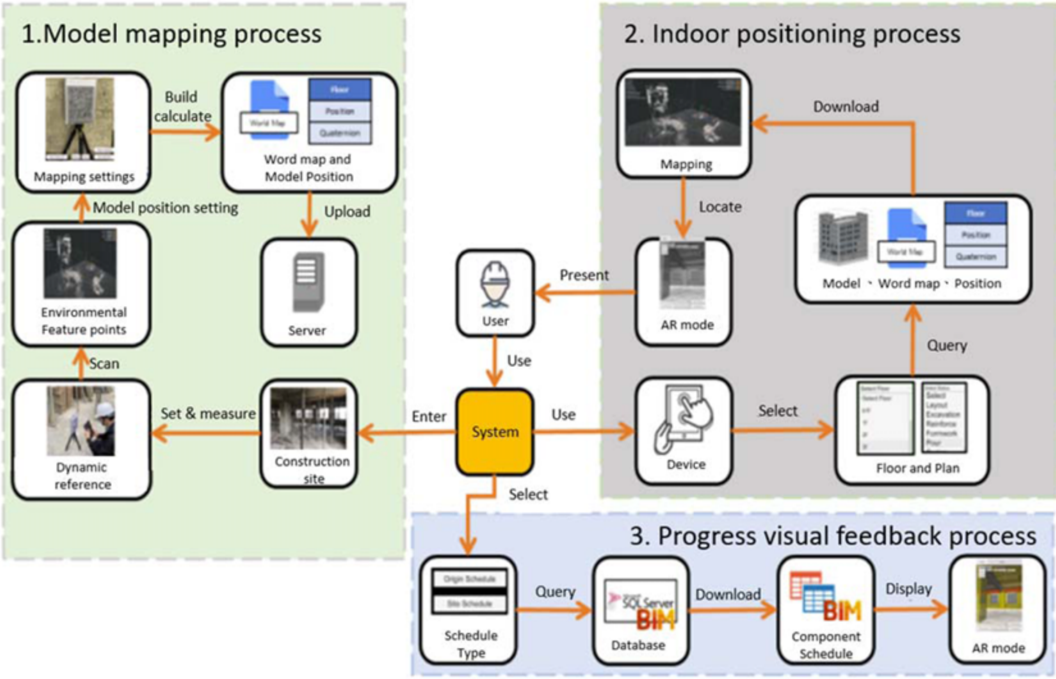


Fig. 13. System Operating Framework

and overlay the model onto the real scene displayed on the equipment screen. The detailed explanation of the current system operation mechanisms for the placement and fitting of the model will be provided in Section 6.1.

3. Visual feedback of system information for construction progress comparison: On the AR/VR integration screen presented by the system, the user can select the model component that corresponds to the required work range for progress management activities on-site. The system will display the progress information import interface related to the selected model component. Upon importing the on-site progress, the system will instantly compare it with the pre-planned progress and present the current status of work progress for each component. Different colors will be used to indicate whether the progress is ahead of schedule, on schedule, or behind schedule. The detailed explanation of the system operation mechanism for visual feedback on construction progress will be provided in Section 6.2.

## 6. System Operation Mechanisms

### 6.1 On-Site Placement and Fitting Mechanism of the Model

In order to align the BIM model accurately on-site, it is essential for the established model to encompass not only fundamental structural and architectural elements but also incorporate a

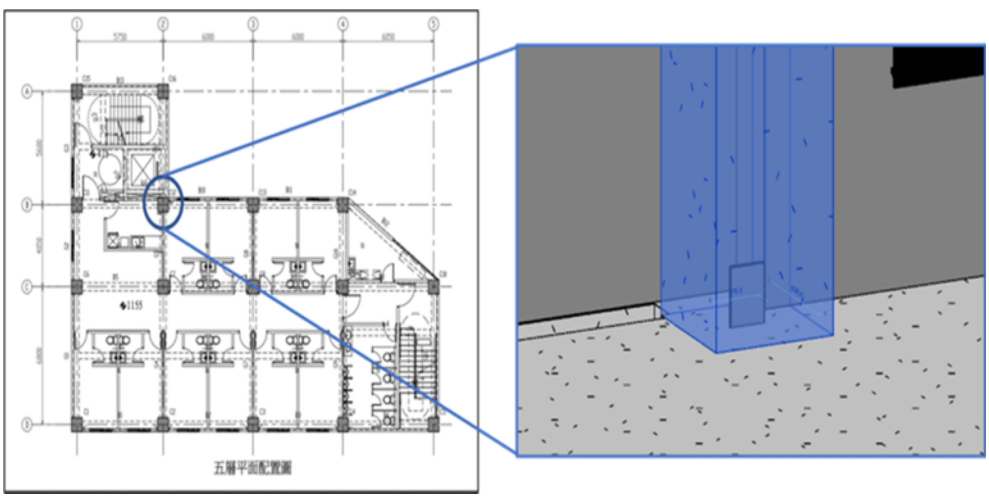


Fig. 14. Creation of a Benchmark Plane Component on the Center Line of an Appropriate Column in the Model

carefully selected column center line to establish a reference plane component on each floor according to the working procedure. This benchmark plane component serves as the foundation for precise model fitting, as shown in Fig. 14.

During the system operation phase, when carrying out model placement and fitting on-site, it is necessary to follow the sequence of steps. Firstly, the setup process involves scanning a feature-point map. Subsequently, the model is placed and fitted in the scene, aligning it with the benchmark plane position. These procedures are sequentially divided into the following four steps:

1. Mounting the dynamic reference plane: After the user enters the site, the dynamic reference plane is mounted according to the position of the benchmark plane established in advance in the BIM model, as shown in Fig. 15. Due to the changing conditions of equipment mounting in the construction site, it is often required to move the position of the dynamic reference plane. Thus, it is required to use leveling and ranging tools continuously for the dynamic reference plane to measure the difference between the position of the mounted dynamic reference plane and the position of the benchmark plane set up in advance in the corresponding BIM model, where the difference is expressed as $d_x$, $d_y$, and $d_z$, as shown in Fig. 16. Finally, the measured distance data is imported from the system screen to provide a basis for subsequent computation model coordinates.
2. Path planning for feature-point scanning: Prior to feature-point scanning, the dynamic reference plane should be taken as a starting point. Based on the recommendations in Section 4.2.1, taking a closed path, the existing objects are scanned and scanning of the floor slab is adopted as a link to plan the scanning path, so as to avoid path interruption. The aim is to cover the effective range of positions (continuity) to the target of this run and if the position drifts during the operation, then the position of the auxiliary reference point can be quickly scanned to correct the scene position.
3. Feature-point map scanning and mapping: According to the location of the user, the floor, construction stage, and dynamic plane component are selected to serve as benchmark placement. Feature-point mapping is conducted following the planned scanning path and method, as shown in Fig. 17. The corresponding spatial information of the feature points extracted in the process will be stored in the. worldmap file format, and the file will be uploaded and stored in the server.
4. BIM model component fitting based on the dynamic reference plane: A corresponding plane component is selected at the location. After loading into the mobile device, placement and fitting of the BIM model are carried out. Using the feature-point spatial information from scanning results, image features on the completely mounted dynamic reference plane are detected to obtain the real physical plane. Then, through the collision detection rays emitted from the center

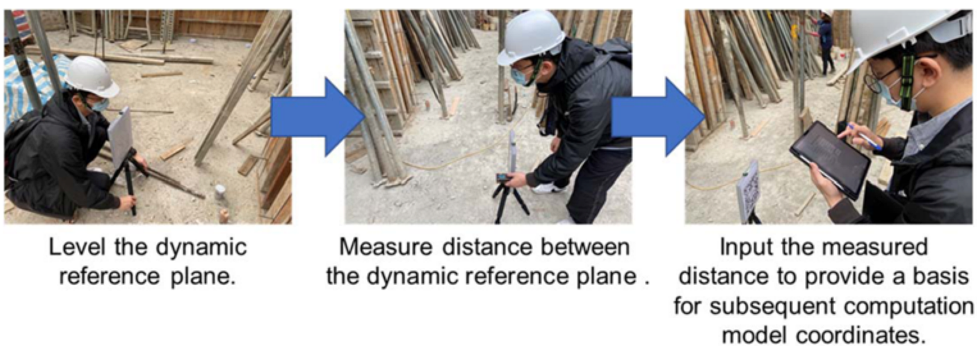


Fig. 15. Flow Chart for Leveling and Mounting of a Dynamic Reference Plane

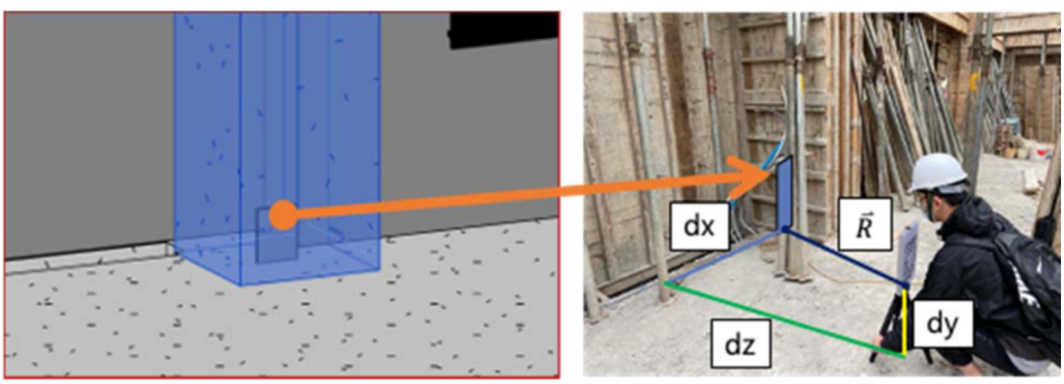


Fig. 16. Measurement of Distance between the Mounting Position of Dynamic Reference Plane and the Corresponding On-Site Position of Benchmark Plane in the Model


**Fig. 17.** Scanning Method for Constructing a Feature-Point Map on Construction Site Using the Proposed System

of camera, the selected plane component is placed on the detected physical plane. Through presentation on the screen of the mobile device and camera, the plane component is accurately placed into the corresponding frame of the dynamic reference plane and the model placement is complete. Currently, coordinate parameters of the BIM model in the scene are obtained according to the position of the placement plane. The process for computation of the BIM model coordinate parameters is as follows:

– When this system loads a model, the BIM model coordinates of the entire floor are fixed and placed remotely in advance at the position array of $P_{model}$ $(x, y, z)$ and the angle array of $Q_{model}$ $[x, y, z, w]$. Currently, the initial position of the benchmark plane component in the model selected from the menu is $P_{plane}$, and the angle is $Q_{plane}$.
– Next, the selected benchmark plane component is placed onto the device screen by operating the camera, that is, it is placed above the frame position of aligned dynamic reference plane. After placement, the position of the benchmark plane component is $P'_{plane}$ and the angle is $Q'_{plane}$.
– In order to calculate the position of the BIM model in a scene, the model needs to be turned to the same angle, so that the relative position of the model in space can be calculated according to the movement distance of the plane component. Using the basic rotation matrix formula, the rotation angle of $\Delta Q$ $[x, y, z, w]$ can be calculated as shown in Eqs. (5) and (6). Next, the model is transformed toward the same direction of the scene according to the resulting $\Delta Q$. The relative position vector of $\vec{P}$ can be obtained according to the difference between the position of the original benchmark plane and that after placement, as shown in Eq. (7). It is used as the basis for obtaining the change in position of a moving model placed on the dynamic reference plane in a scene, as shown in Fig. 18.

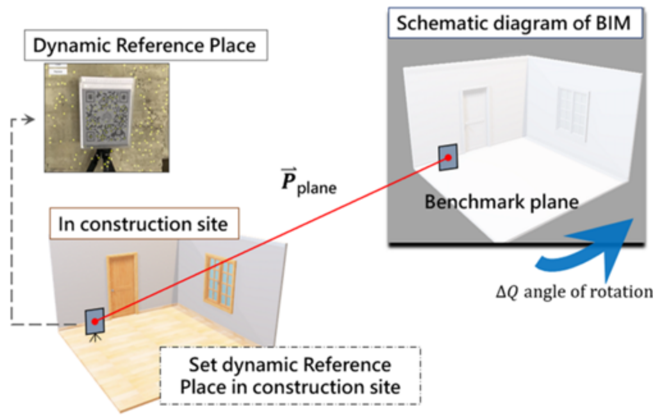


**Fig. 18.** Rotating the Model Toward the Same Direction as the Real Scene at First, so that the Remaining Translation Offset of Each Model Component are Equal to the One of the Benchmark Plane

$$Q'_{plane}[x', y', z', w'] = \Delta Q * Q_{plane}[x, y, z, w] \tag{5}$$

$$\Delta Q = Q'_{plane} * Q^{-1}_{plane} \tag{6}$$

$$\vec{P} = P'_{plane} - P_{plane} . \tag{7}$$

– However, the model is not yet fitted to the correct position in the scene, only the relative position when placed on the dynamic reference plane is calculated. Therefore, it is still required to add up the distance vector of $\vec{R}$ $(d_x, d_y, d_z)$ between the benchmark plane and dynamic reference plane measured in the aforementioned model-fitting mechanism step, so that the absolute position of the BIM model in the real scene can be obtained according to the component position vector of $\vec{P}$, as shown in Eq. (8). Finally, the resulting rotation angle of $\Delta Q$ and position vector of $\vec{P}$ are uploaded to the database for storage. The model is subsequently downloaded and placed at the fitting position in the scene.

$$\vec{P} = P'_{plane} - P_{plane} + \vec{R} \tag{8}$$

– Finally, the resulting rotation angle of $\Delta Q$ and the position movement vector of $\vec{P}$ are uploaded to the database for storage. They are used as the basis for transformation when placing the model at the fitting position in the scene when the model is subsequently downloaded.

### 6.2 Visual Presentation for Comparison of Construction Progress

This research developed a prototype system integrating SLAM-based AR and BIM, incorporating the concept of 4D construction and planning management, and providing a visualization of progress management in an indoor construction site. It follows the on-site completion status of work items corresponding to BIM components, as well as the progress of the preset schedule corresponding to the current date for comparison. The progress comparison results are presented in different colors on the BIM in order to display them with visualized feedback. Again, by integrating the BIM model and AR, the virtual superimposed image is displayed on the real construction site scene, making it more intuitively demonstrated to the user through visualization and helping them to quickly comprehend the on-site work progress.

The operating mechanism for taking visualization feedback is shown in Fig. 19. The progress of various components can be subdivided into different work stages. For example, construction activities involving RC structural components can be divided into lifting, rebar assembly, formwork assembly, grouting, mold removal, curing, and other stages, so the weighting values for completion of each stage of work can be assigned based on the contract requirements.

The system can automatically calculate the plan and actual progress percentages of the work item based on the scheduled completion date of each work item, as well as the actual completion date entered in the system on-site, thus determining whether each work item is falling behind schedule. For construction activity items falling behind schedule, the corresponding model components are marked in red to alert users. For activity items that are on schedule, the corresponding model components are presented in yellow and those that are ahead are presented in green. This presentation mode allows users to comprehend at a glance whether progress is behind schedule and take appropriate steps immediately.

## 7. System Validation

In this research, the system was applied in five different scenarios within an indoor construction site. The scenarios include automatic fitting of BIM models and on-site query of component progress, form filling for inspection of on-site work progress of a component, comparative switching for the difference between originally planned and actual activity progress, visual presentation of components affected by progress, and a 4D construction simulation in AR mode on-site, in order to validate the system feasibility of this system.

### 7.1 BIM Model Automatic Fitting and On-Site Query of Component Progress

As previously mentioned, prior to utilizing and operating the system, the user is required to undertake several steps. These include planning a designated path for the AR system, mounting a dynamic reference plane at the construction site, and accurately measuring the distance parameters based on the position of the plane. Subsequently, the user opens the system and selects the desired location and viewing stage from the menu to initiate the scanning process of environmental feature points for mapping purposes. Once completed, the user proceeds to place the BIM model plane component onto the dynamic reference plane and taps to upload the feature-point map and model positioning information. Upon re-entering the designated space, the system will automatically identify the environment through SLAM technology, allowing for equipment positioning and the fitting presentation of the BIM model. Additionally, users have the option to tap on the component model to download and view the pre-defined progress schedule, facilitating comparison with the actual construction status in the current stage. This process is shown in Fig. 20.

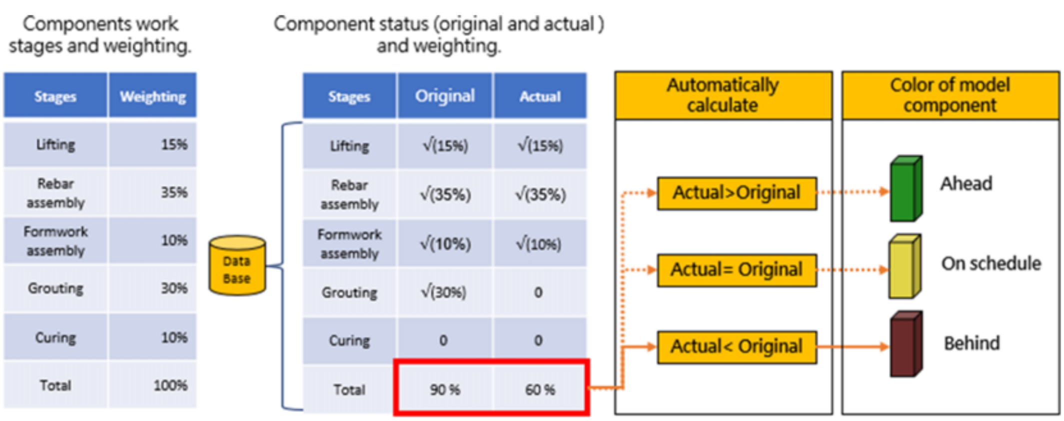


**Fig. 19.** Operating Mechanism to Visualize Alerts for Construction Progresses of Work Items

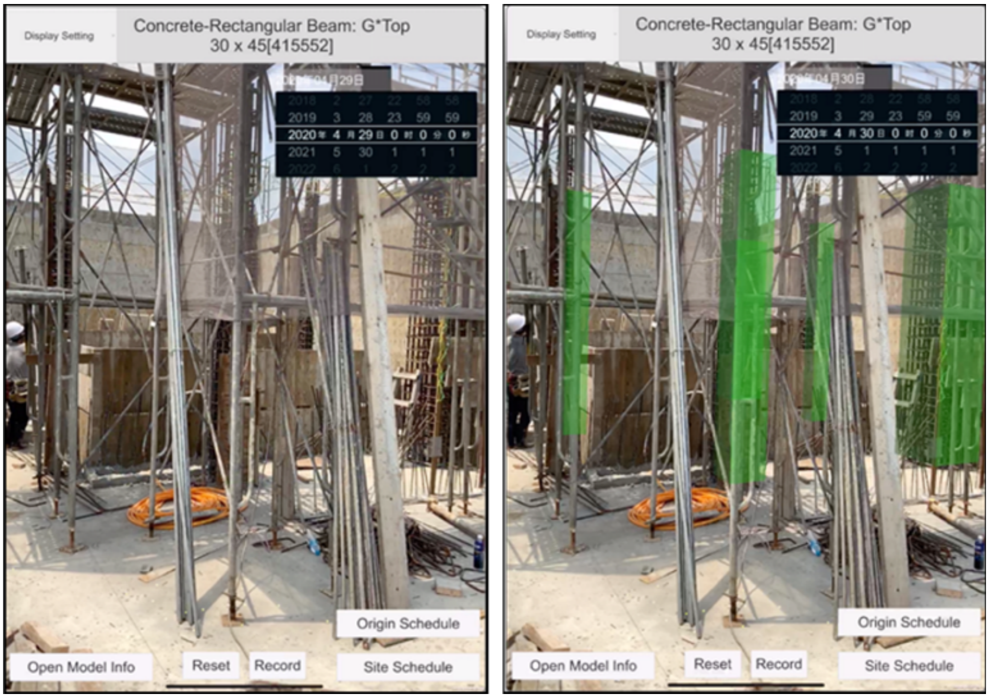


**Fig. 20.** Automatic Overlaying of the BIM Model on the Real Scene and Then Displaying Component Progress On-Site

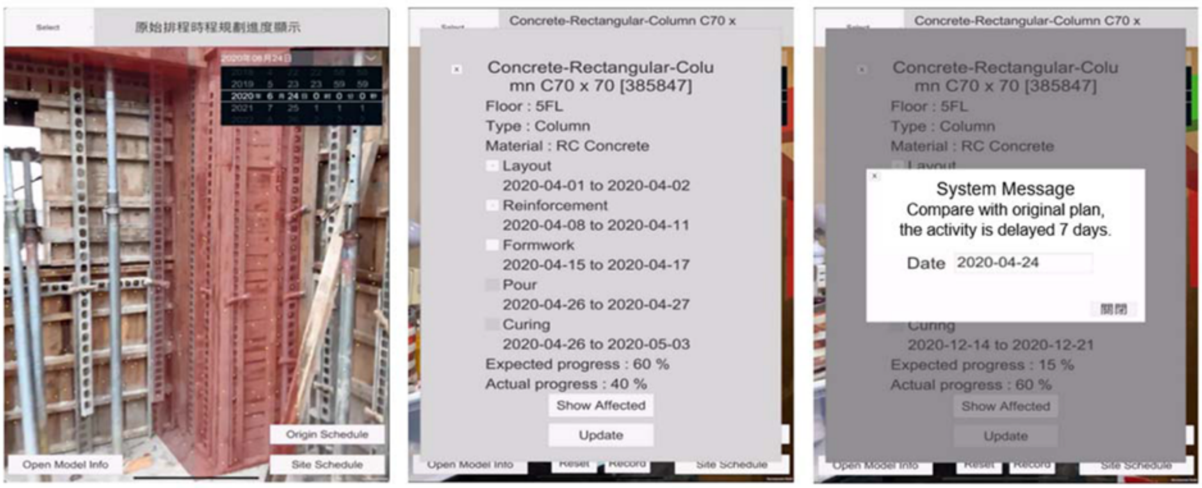


**Fig. 21.** Form Filling for Inspection of On-Site Work Progress of Each Component

## 7.2 Form Filling for Inspection of On-Site Work Progress of Components

During the implementation of this system for progress management at the construction site, the site engineer is responsible for inspecting the relevant components of each activity item individually and completing an on-site progress report. To streamline this process, the system provides the capability for users to select an object through the AR screen, which will open the corresponding inspection form. The engineer can then assess the on-site situation of each construction component and mark the completed work items on the form accordingly.

To ensure effective progress monitoring, the system compares the actual completion date recorded during the on-site inspection with the forecast completion date from the schedule. It evaluates whether the progress is ahead or behind schedule and notifies the user through reminders. In the case where a component has surpassed the forecast completion date, the system will issue an alert specifying the number of days by which the schedule needs to be extended. Simultaneously, the dates of subsequent construction work items will be updated to accommodate the necessary adjustments based on the progress. This mechanism allows for the ongoing refinement of the forecast plan in accordance with the actual progress achieved. A visual representation of this process is shown in Fig. 21.

### 7.3 Comparative Switching on the Difference between Original and Forecast Activity Progress

During the course of a construction project, various factors can lead to delays in project progress, resulting in discrepancies between the original plan and the adjusted forecast plan. To address this, the system provides continuous updates to the forecast plan based on the filled reports of on-site construction progress.

By importing two sets of schedules, namely the original plan progress and the forecast plan, the system enables real-time comparison with the on-site progress. Taking the example of a concrete beam structure under construction, the system retrieves the original and forecast plan dates for the selected components and presents the corresponding progress status separately.

In Fig. 22, the progress of the component in the forecast plan is presented in yellow, indicating that it is on schedule. On the other hand, the red color indicates that the progress in the original plan is behind schedule. By comparing the two schedules, the user can take appropriate measures to ensure that the forecast plan aligns with or exceeds the original plan, enabling the completion of work as anticipated.

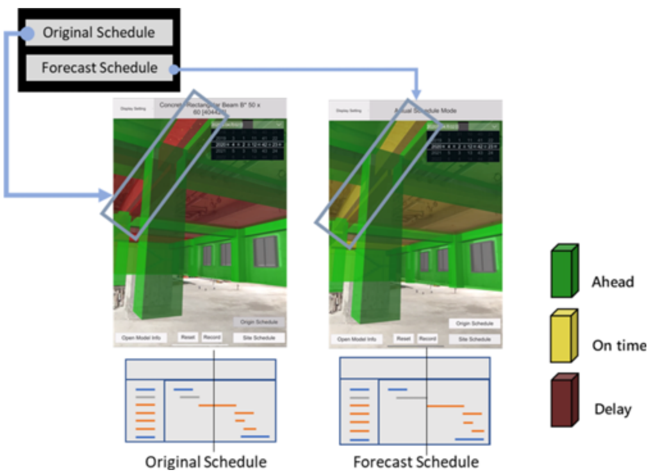


**Fig. 22.** Comparative Switching for the Differences of On-Site Work Progresses between Original and Forecast Schedule

### 7.4 Visualization Presentation of Components Affected by Working Process

The relationships between activities within a project can be classified as predecessors, successors, parallel, or dummy. Delays in predecessor activities can impact the progress of successor activities. If immediate adjustments cannot be made to the successor activity, it can lead to cumulative effects and delays in the overall project progress.

This system allows users to monitor the work progress of on-site components. When a particular activity is identified as falling behind schedule, users can access the relevant components of the affected successor activities. By selecting the component on the AR screen and tapping the affected button in the component information form, the system will display the relevant components associated with the affected successor activities. Taking a concrete beam structure under construction as an example, the operation screens of this function are shown in Fig. 23.

### 7.5 4D Construction Simulation in AR Mode On-Site

Each component on the construction site is associated with an activity schedule and working sequences. To provide users with a clear understanding of the construction progress, a visualized animation of the planned work sequence is called a 4D construction simulation. This simulation helps users gain an intuitive understanding of the sequential development of subsequent construction activities. As part of this system's functionality, a feature is provided to present a 4D construction simulation in AR mode on the construction site. By selecting a time range, the simulated construction process is dynamically displayed on an VR-integrated screen, as shown in Fig. 24. In this mode, users can observe the positions of various structural components and verify the accuracy of on-site work progress. Additionally, users can comprehend future work items through the dynamic simulation, enabling them to plan and allocate resources for on-site configuration and workflow.

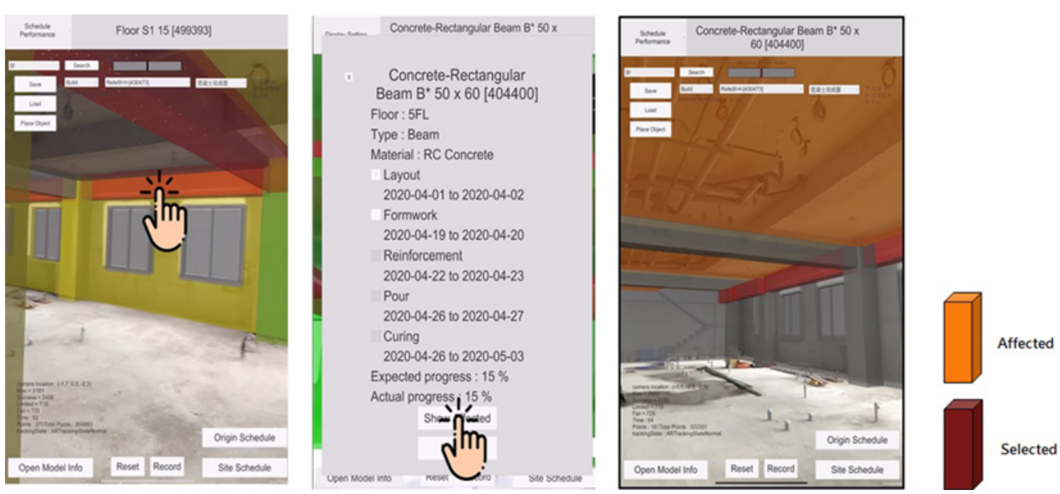


**Fig. 23.** Visual Presentation of the Subsequent Components Affected by the Working Progress of a Selected Component

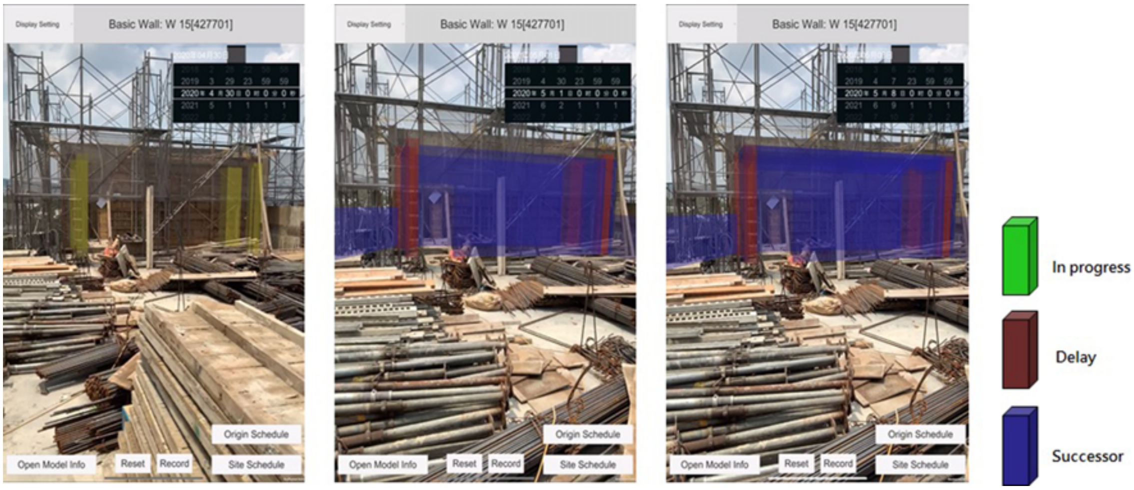


**Fig. 24.** 4D Construction Simulation in the AR Mode On-Site

## 8. Conclusions

During the construction phase of a building, the dynamic variations in the construction site environment and the monotonous texture conditions present challenges to the feature point scanning and model placement methods. These factors lead to a decline in positioning accuracy, resulting in significant deviations in the alignment of the augmented reality (AR) system's displayed model after accumulated positional offsets and scanning errors during movement.

Utilizing the ARKit augmented reality (AR) system development platform on iOS handheld devices, along with its integrated simultaneous localization and mapping (SLAM) positioning technology, this research has developed an immersive on-site visual construction management system. By leveraging SLAM, which is particularly suited for AR presentations in indoor construction environments, the system achieves accurate alignment of the building information modeling (BIM) model within the physical construction site.

Furthermore, it incorporates a visual progress management mode that facilitates a comprehensive comparison between real-time on-site progress and the scheduled construction timeline. Within the augmented reality mode, the visual progress management mode adopts an intuitive operating mechanism to facilitate tasks such as recording project progress, managing daily activities, and providing feedback on progress information. The ultimate objective is to create a visually immersive mode with seamless AR integration that enhances the efficiency of on-site construction management.

The theoretical contribution of this research is the utilization of SLAM technology in AR presentations for indoor construction sites offers several operational recommendations. These recommendations include feature-point scanning and closed path planning, optimal movement rate during scanning, model placement benchmarks, fitting on the construction site, and the update frequency of the feature-point map. Through rigorous testing and validation in real-world indoor construction sites, the proposed system successfully achieved accurate fitting of BIM models, while keeping fitting errors within acceptable limits during practical applications.

From an industrial perspective, the system's 4D progress management mode, which compares real-time on-site progress with the construction schedule by presenting the BIM model in the AR mode, was tested across five different application scenarios. These scenarios demonstrate the system's functionalities, allowing users to interact with the BIM model within the AR environment. By providing simultaneous, real-time, and intuitive feedback, the system enables efficient collection of work progress and facilitates real-time visual comparison of construction progress. This empowers site engineers to enhance their comprehension and decision-making processes in a swift and effective manner.

However, there are some limitations and opportunities for improvement. The system's reliance on feature-point mapping and scanning may be affected by environmental conditions, such as poor lighting or occlusions. Additionally, the system's effectiveness in large-scale construction projects and its integration with existing project management software could be explored further.

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