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INTEGRATION OF BIM AND AR WITH VSLAM TO ASSIST IN CONSTRUCTION SITE INSPECTION

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Abstract. Building Information Modeling (BIM) has been widely adopted for construction inspections due to its ability to integrate multiple data sources. Engineers use BIM to identify and review site issues, yet inspection systems face several challenges. Firstly, positioning inspection areas on a construction site using BIM with Augmented Reality (AR) requires complex model manipulation. Additionally, signal or Internet connectivity issues may limit positioning technologies. Secondly, human error or interference is common in traditional inspection processes due to their complexity.

To overcome these barriers, this research applied BIM and AR with Visual Simultaneous Localization and Mapping (VSLAM) to help inspectors quickly and effectively record construction defects as photographs with notes and their locations. An efficient approach is proposed to integrate BIM and AR with VSLAM, and a prototype is developed to validate and demonstrate how the proposed system can assist a site inspector in performing quality management, even offline. The system uses a two-phase indoor positioning method: initial localization via visual markers and real-time tracking with VSLAM, enabling precise defect tracking and efficient model adjustments. While significantly improving inspection accuracy and efficiency, its performance is affected by environmental factors like lighting and marker placement, providing insights for future refinement.

Keywords: Building Information Modeling (BIM), Visual Simultaneous Localization and Mapping (VSLAM), Augmented Reality (AR), construction site inspection.

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1. Introduction

Construction quality management is the process of quality control on a work site, ensuring that all parts of a project comply with the standards and are safe to use (such as the materials, regulatory requirements, etc.). Effective quality inspection plays a crucial role in quality management throughout the whole phase of the construction process. Quality inspection tests the quality of the construction and installation activities (e.g., concreting, piling, door installation, etc.) during each construction phase, e.g., on-site inspection, field testing, and material sampling of the soils, concrete, etc. In general, an inspector collects defect information (e.g., image, location, defect type, parties involved, notes, etc.) when they find a defective item on a construction site.

Typically, on-site construction quality inspection is manually conducted, and construction quality information still needs to be recorded on paper, which risks document loss and data manipulation, jeopardizing quality accountability (Wu et al., 2021). Many researchers have suggested that advances in information technology, such as the internet, databases, and web-based collaboration tools, could improve documentation and communication in the quality systems process (Chin et al., 2004; Ma et al., 2018).

Certain barriers exist, however, in current inspection practices, and Lin and Dzeng (2019) have reported several problems in traditional practices for quality inspection:

1. The inspector can falsify inspection item records for convenience.
2. Filing errors can occur since the inspector uses a camera to take photos and record information about the defective item on paper. Therefore, there is a relatively high chance that the inspector could subsequently forget the location of a defective item.
3. There can be no relevant documents to refer to in the future since the data might not have been correctly saved.

Of these issues, defect location accuracy is vital to the inspection process. Generally, an inspector will record defect information in on-site documents and digitalize the records later in their office. Consequently, they may not remember the exact locations of defects and make mistakes when re-entering the information into a defect management form based on their on-site records (Kwon et al., 2014). Furthermore, documenting the inspection records using only text and 2D images is insufficient to describe the exact position of defects in a 3D environment, which often leads to misunderstandings and construction errors (Lin et al., 2016).

To address these challenges, Zhang et al. (2025) applied emerging technologies like UAVs equipped with high-resolution cameras and thermal sensors, which can provide precise, real-time defect location data, improving accuracy and reducing human error. UAVs can capture 3D imagery and integrate with systems, allowing inspectors to visually pinpoint defects in a comprehensive 3D model, which significantly enhances defect management and reduces misunderstandings. Furthermore, accurate defect location records are essential for effective information management. Without them, it becomes difficult to categorize and manage defect data collected on-site. As a result, the demand for high-quality inspection has driven the development and application of smart construction sites, where efficient defect data management is crucial.

Several investigators have explored the possibility of more accurate inspection results utilizing visualization technologies such as Building Information Modelling (BIM) and Augmented Reality (AR). For example, Lai et al. (2024) demonstrated how Digital Twin (DT)-based methods integrating 3D models, sensor technologies, and finite element models significantly enhance structural health monitoring of bridges. This showcases the potential of integrating advanced technologies to improve accuracy and efficiency in construction management tasks. Over the past few decades, BIM has become the most frequently used technology for visualizing and coordinating architecture, engineering, and construction (AEC) work, avoiding errors and omissions, improving productivity and management of construction projects, etc. (Chen & Luo, 2014). AR can combine the virtual and real world on one device, such as in the virtual text, graphics, or by the superimposition of 3D models on actual images.

Similarly, AR has been shown to dramatically enhance interaction between users and industrial systems by overlaying real-time data and virtual elements onto the physical environment. For instance, Li et al. (2019) developed an AR-aided smart sensing system for in-line condition monitoring of IGBT wafers, integrating infrared-visual fusion to improve defect detection efficiency and throughput. These capabilities demonstrate AR's potential to augment defect inspection processes, enabling more precise and intuitive construction site management. Building on this, Tan et al. (2024) proposed a comprehensive framework that integrates computer vision, AR, and BIM to enhance defect inspection and management in construction. Their AR-based defect inspection application effectively detects and tracks defects, while the BIM-based data management platform consolidates inspection data for streamlined documentation. This integration not only facilitates real-time tracking but also addresses key challenges in data integration and process efficiency, achieving a 78.63% increase in inspection efficiency compared to traditional methods. Furthermore, Adebowale and Agumba (2022) systematically reviewed AR applications in construction and identified six key categories where AR improves productivity, including monitoring, training, safety management, and assembly processes. Their findings highlighted that AR enhances real-time progress tracking, reduces errors, and improves communication across construction teams, underscoring its role in boosting overall site productivity and efficiency.

Building on these advancements, Lin et al. (2016) utilized BIM and web technologies to integrate defect information to increase the quality of defect inspection. This system combines the defects reported by inspectors into a BIM model and improves efficiency, especially concerning communication between the construction sites and the office. Chi et al. (2019) developed a BIM-based AR quality inspection system that applies BIM and AR to quality inspection. Of particular interest was a comparison of the differences between the BIM model components and the real objects, e.g., the inspectors were to check the size of the openings (door and window) to make sure they matched the requirements.

Tracking the real-world environment and registering virtual information are fundamental functions of an AR system. AR registration involves aligning and integrating virtual objects or information into the physical environment. Tracking in AR technology refers to dynamic sensing and measuring of spatial properties. Dynamic sensing involves real-time tracking of the user's position and orientation, accurately projecting virtual objects or information into the real environment. However, calibration is challenging while implementing AR. For example, Sydora and Stroulia (2018) mentioned that a 3D model drifts when the users walk too long or fast without recalibrating, and the computer-generated scene tends to get out-of-sync with the real-world scene. Ashour and Yan's (2020) research addressed the challenges of AR tracking and registration in physical environments. They developed the system prototype that features a user-friendly interface with a slide bar for adjusting translation and rotation along the x, y, and z axes during the initial registration, and the slide bar can assist the model in aligning with the real-world environment. However, adjusting the position of the model created by the AR is time-consuming, requiring manual rotation and transformation to ensure that it is correctly superimposed on the actual environment onscreen, and this method is only for the initialization process. For example, Chi et al. (2019) employed AR and BIM technologies to assist inspectors in construction site inspections. Their approach requires model adjustment at each inspection place during the inspection process. However, these techniques require a subsequent matching process with the 3D model, particularly in long baseline cases.

Visual Simultaneous Localization and Mapping (VSLAM) technologies have rapidly developed. Via VSLAM, users can use a camera and IMU (inertial measurement unit) to build a map of an unknown environment. By integrating the functions of VSLAM, a model's position can be quickly adjusted during use according to the environmental factors it senses. For example, VSLAM computes spatial information (such as the relative position of the wall and the floor) of the environment using data collected by various sensors and fine-tunes the BIM model position in real time. Acharya et al. (2019) presented a visual indoor localization approach by matching image sequences captured by a camera with VSLAM. The results indicated that it could improve localization and tracking accuracy. Liu et al. (2020) presented an approach to address indoor positioning accuracy using BIM for project maintenance when coupled with an on-site inspection. They utilized AR technology based on VSLAM and reported that incorporating VSLAM can enhance the stability of the integration of the virtual and actual worlds. In summary, VSLAM could serve as an indoor positioning method and be crucial in improving AR accuracy for an on-site inspection, but it must be continuously calibrated afterward. Many studies have utilized AR technology to integrate BIM into construction site environments. However, AR applications still face several challenges, including accurately determining the user's position and aligning virtual data with real data (Calderon-Hernandez & Brioso, 2018). The AR system tends to encounter computational errors when moving.

To address the issues mentioned above and enhance the inspection process's effectiveness and efficiency, this research aims to develop an efficient approach to integrating BIM and AR with VSLAM to ease an on-site manager's work and enhance task delivery efficiency for construction site inspection. A system framework is proposed and used to prototype a BIM-based quality inspection system for testing and demonstration. The system framework proposed in this study for a BIM-based quality inspection system includes two core modules, including an adjustment module and an indoor positioning module, to address three key challenges. First, the most frequently adopted positioning technology, RSSI-based (Received Signal Strength Indication) indoor localization techniques, such as BLE, Wi-Fi, and Zigbee, can have cost issues and weak signal problems on-site. Thus, this research utilizes a two-phase indoor positioning approach, including initial and real-time localization. The initial localization is achieved by a marker-based method. In contrast, real-time localization uses VIO (Visual-Inertial Odometry) and AR with VSLAM to project a 3D model in the real environment in real-time. Second, this study proposes a method for VSLAM-based model calibration as the core technology to correct tracking errors during movement. Third, the traditional inspection process should be improved by embedding BIM technology.

Despite these advancements, several gaps remain in integrating BIM, AR, and VSLAM for construction site inspections. Current systems face challenges such as:

(1) Ensuring accurate indoor positioning in environments without signal infrastructure.
(2) Aligning and calibrating BIM models with physical environments in real-time during inspection tasks.
(3) Tracking defects efficiently and managing data to minimize human error in construction scenarios.

To address these challenges, this study proposes and validates a novel system framework to enhance the efficiency and accuracy of construction site inspections while mitigating common issues found in traditional methods.

The paper is arranged as follows. Section 2 first provides an overview of construction site inspection systems and BIM applications for construction site inspection, especially in defect inspection. Then, it discusses common indoor positioning techniques, such as iBeacon, RSSI fingerprint, and RFID (Radio Frequency Identification), needed for site inspection. Finally, it reviews the VSLAM technique. Section 3 presents the integration of BIM and AR with VSLAM for site inspection. Then, in Section 4, this research proposes the framework and system procedure of the BIM-based quality inspection system prototyped for validation and demonstration. Section 5 presents a case study for system validation at a construction site for social housing in Taipei. Finally, Section 6 concludes this research and discusses future research directions.

2. Related works

Tsai and Hsieh (2016) reported that BIM-enabled construction inspection includes four components: BIM modeling tools, mobile devices (smart devices, wearable devices, etc.), construction inspection databases, and management websites. BIM modeling tools and management websites serve inspectors in an office environment. The construction inspection database integrates all the data with the different components, and the inspector uses a mobile device to record data at the construction site. Since BIM supports construction inspection, it can simplify traditional inspection procedures. Figure 1 shows how inspectors can collect and integrate information using mobile devices during the inspection. After reviewing the literature concerning construction site inspection systems, BIM for construction site inspection, and common indoor positioning techniques used on construction sites, the authors have identified several research gaps and potentials, including locating the defective construction item in real-time within construction site environments and accurately projecting the BIM model through AR during the user movement. Based on this identification, this research proposes an indoor positioning strategy and model adjustment method that combines BIM and AR with VSLAM to assist an inspector in collecting defective item data at a construction site.

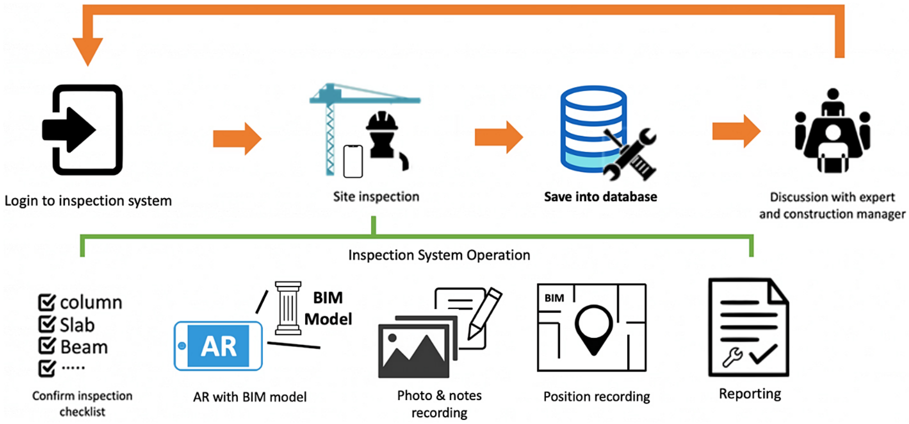

Figure 1. BIM-based inspection system's roles in assisting construction inspection (adopted from Baiburin, 2017)

2.1. Systems for construction site inspection

Quality management is essential to the construction process, significantly impacting construction costs and outcomes; however, problems frequently occur during the quality inspection, such as the execution of trivial and time-consuming processes and repeated documentation (Herrera et al., 2019). Generally, construction defects can be classified into two types: patent defects and latent defects. A patent defect usually occurs because of design errors and human negligence during construction. Patent defects include design errors, poor quality of materials and products, low quality of installation work, operational deficiencies, and a combination. Baiburin (2017) found that 42% of defects occurred from the low quality of the installation work, which is the most common patent defect. A latent defect occurs after the construction phase and is often not obvious (Gashi, 2018).

Recent construction detection techniques, such as Unmanned Aerial Vehicles (UAVs), Robots, and Infrared Thermography (IRT), etc., have improved the detection of patent defects like design errors, poor material quality, and installation flaws. For example, IRT is effective in identifying surface defects such as delamination, while UAVs and robots can be equipped with various sensors to inspect hard-to-reach areas and assess structural conditions more efficiently (Ibrahim et al., 2024). However, these methods often work independently, focusing on specific defect types without providing a comprehensive overview of the construction quality. Despite these technological advancements, many challenges in construction quality management remain unresolved, particularly in the areas of data integration and process efficiency. Effective quality management not only relies on detecting defects but also requires comprehensive systems that can consolidate inspection data, facilitate real-time tracking, and streamline documentation processes. According to Lin et al. (2016), five problems should be addressed for construction quality inspection in Taiwan: (1) low efficiency due to high dependence on paperwork; (2) poor management of defect work data; (3) poor control of historical work data due to high dependence on 2D drawings; (4) failure to provide complete defect work data; and (5) lack of platforms that can provide efficient service for quality inspection and audit work.

Chowdhury et al. (2019) reported that mobile technologies offer the potential for significant improvements in reducing construction time and cost, defects, accidents, waste, and operational and maintenance costs while improving predictability and productivity. For example, a smartphone could help create and store ongoing construction project information and retrieve stored data for related management activities. Alizadehsalehi et al. (2020) pointed out that combining XR and BIM provides interactive renderings, spatial coordination, and virtual mockups. The benefits of using BIM and XR together can enhance the performance of AEC projects in the whole project life cycle, including timesaving, cost, and quality.

To clarify the degree of BIM and mobile technologies implementation across on-site inspection systems, this paper compared different site inspection systems with embedded BIM and mobile technologies, including three features: inspection documentation, BIM model, and system cost (as shown in Table 1). Generally, the pre-processing of BIM models is a complex task that involves extracting and processing BIM data. AR pre-processing is also required to use augmented reality (AR) to overlay a 3D BIM model (denoted as the AR-BIM model herein) on a construction site. This involves preparing the BIM data in a format compatible with AR software and ensuring the model is accurate and current. Generally, after the BIM model is established by BIM software (such as Revit), the geometric and non-geometric information in the BIM model must be extracted through a conversion process to meet the format required by the device.

Moreover, the system needs to provide a positioning mechanism to allow the AR application to recognize the location and direction in the real world. Some on-site inspection systems can locate user positions through indoor positioning technology, allowing users to search for a specific object or record the location of a defective item. Some research (e.g., Ma et al., 2018; Liu et al., 2020), has reported that indoor positioning is critical for a construction quality inspection system to guide the inspector to the target object for inspection. However, most indoor positioning techniques are wireless network-based systems using ultrasonic tracking, electromagnetic tracking (UWB, RFID, WLAN/Wi-Fi, etc.), and RSSI-based tracking. They are often unsuitable for a construction site because wireless network signals are blocked or interfered with on-site equipment and laborers. Therefore, an on-site system should consider offline support to ensure critical tools always remain available to workers. It will synchronize its data with the backend database when it is back online.

2.2. Building Information Modelling (BIM) for construction site inspection

Many researchers have utilized BIM for data and system integration (see Table 2). For example, Pratheesh Kumar et al. (2020) integrated BIM with AR to visualize real-time construction activity. In addition, they reported that an AR-based system integrated with BIM helps site engineers better understand the construction process and improves construction defect management.

This study uses BIM to record indoor positions with spatial data during inspection (more discussions can be found in Section 3.1.2). Furthermore, by combining 3D visualization of BIM and AR technologies, inspectors can identify patent defects by overlapping on-site work and virtual models. Moreover, since a BIM model can contain rich project information, it can be used as a data container for real-time data review to assist on-site inspectors.

2.3. Common indoor positioning techniques used on construction sites

Location-aware information at construction sites is an emerging research area that focuses on the automatic delivery of spatial information about the location of the materials, workforce, and equipment on site for better construction management (Ratajczak et al., 2019). The primary worldwide outdoor positioning technique is the Global Positioning System (GPS) from the Global Navigation Satellite Systems (GNSS); however, environmental conditions affect its accuracy (such as the presence of walls and rebars on-

Table 1. Comparison of BIM-based construction site inspection systems

Feature of systems		BIMInspector (Ma et al., 2018)	BIMDM System (Lin et al., 2016)	Onsite BIM system (Liu et al., 2020)	BIM-AR QM Web-Based System (Mirshokraei et al., 2019)
Inspection documentation	Mobile device	Not specified	Webcam-enabled tablets	iPhone	iPhone
	Defect markable	Yes	Yes	No	Yes
	Photo-storable	No	Yes	No	Yes
	Indoor positioning	Combining magnetic field and Wi-Fi signals	No	BLE technology	No
	Offline support	No	The defect information can temporarily be stored on the device	No	No
BIM model	Web-Viewer	Yes	Yes	No	Yes
	Augmented Reality	No	No	Yes	Yes
	AR Model Pre-process	No	No	High	Medium
System cost		High	Low	Medium-high	Medium

Table 2. BIM support in the construction phase

Operation Phases	Major Challenges	Proposed Solutions	Reference
Onsite inspection	Difficulty finding the defect locations	Using spatial data of BIM and MR to label the defect locations	Ma et al. (2018), Vasilyev et al. (2019), Nguyen et al. (2018), Sidani et al. (2021)
	Errors in records caused by a delayed notation of defects	Using the BIM model and digital forms to store the defective work data in real-time on a device or cloud database for future arrangement	Ma et al. (2018), Achkar (2016)
Data processing after inspections	Time-consuming data arrangement	Using a digital system to arrange data and categorize information, reducing the manual arrangement process	Ma et al. (2018), Achkar (2016), Tsai et al. (2014)
	Inefficient communication is caused by the limited ability to describe a situation using words	Using BIM models to locate and visualize the defects in detail with XR	Herbers and König (2019), Shi et al. (2020)

site); thus, it is not ideal for indoor positioning. Typical indoor positioning techniques include iBeacon, UWB, RFID, and Visual Markers. Their features and a comparison between these techniques are described below (as shown in Table 3).

2.3.1. iBeacon

iBeacon is based on Bluetooth Low Energy (BLE) radio technology and small transmitters. It transmits a specific unlimited signal in a particular period and carries a MAC Address. Any device equipped with Bluetooth can receive this signal. Many researchers have discussed applying this technology to construction sites (Zhuang, 2020), such as managing site personnel and objects (Dror et al., 2019; Song et al., 2018). Song et al. (2018) proved that the distance could be converted based on the RSSI signal using triangulation; however, in the ordinarily volatile environment of construction sites, Bluetooth signals are easily affected, and because its signal range covers only approximately two meters, many Beacon devices would have to be installed on a construction site, leading to an increase in cost. Mohanty et al. (2020) further demonstrated that BLE-based sensor networks could track worker movement and productivity in construction sites with a location accuracy range of 5–10 meters, depending on receiver gateway placement. Although the system offers portability and cost advantages for smaller sites, the precision of BLE systems is still constrained by environmental factors such as signal interference and multipath effects, particularly in complex and dynamic construction environments.

2.3.2. Ultra-Wideband (UWB)

Ultra-wideband (UWB) technology is a short-range wireless communication protocol that operates at extremely high radio waves with highly accurate characteristics and transmission speeds. For many years, the UWB positioning system has been widely used in the manufacturing industry and is often applied to track the indoor position of personnel. Its ability to provide sub-decimeter accuracy and operate under non-line-of-sight conditions makes it a promising solution for dynamic environments. However, Umer and Siddiqui (2020) pointed out that, for construction sites, UWB technology comes with challenges due to the busier and more dynamic nature of the environment than manufacturing settings. Under constantly changing site conditions, signals often require intermittent recalibration, which affects system performance and accuracy.

Furthermore, Rao et al. (2022) reviewed UWB applications and highlighted their robustness against multipath fading and interference, which are common in construction environments. However, their study also pointed out that on-site environmental factors such as clutter and material properties can significantly influence signal stability, further complicating its deployment in dynamic construction contexts. Finally, Park et al. (2016) noted that UWB systems are relatively costly, making them less suitable for large construction sites.

2.3.3. Radio Frequency Identification (RFID)

RFID is a radio frequency identification technology composed of an RFID reader and transponder, commonly known as electronic tags, connected by integrating intermediary software systems. The principle of operation is that the RFID reader emits a radio wave of a specific frequency to the sensor. The radio wave drives the circuit inside the sensor to transmit its internal data back to the RFID reader. Li and Becerik-Gerber (2011) compared different indoor positioning technologies and summarized eight factors that affect the performance of internal positioning, i.e., positioning accuracy, affordability, line of sight, wireless communication, context independence, data storage, power supply, and applicability to the construction industry. They reported that RFID is a suitable method for application on construction sites; however, the environment rapidly affects RFID signals, so some scholars have combined them with other technologies (e.g., ultrasound) to improve indoor positioning results.

Wei et al. (2023) reviewed various indoor positioning techniques and highlighted the RSSI-based location fingerprinting method as an effective approach for RFID indoor positioning. Their analysis suggests that combining signal filtering, clustering, and optimization techniques can improve the accuracy and reliability of RSSI-based systems, making them more practical for dynamic environments such as construction sites. These findings align with the broader potential of RFID-based sensors, which, as a type of wireless passive sensor, exhibit significant advantages in various fields due to their affordability, reliability, wireless communication capability, and extensibility enabled by their rich data dimensions. These characteristics make RFID particularly valuable in the Internet of Things (IoT) and ambient intelligence systems (AIS), where large-scale, integrated deployments are required. In addition to the methods discussed, Omer and Tian (2018) addressed some of these challenges by leveraging the relationship between the Received Signal Strength Indicator (RSSI) and Radar Cross Section (RCS) for indoor distance estimation. Their study demonstrates that using RSSI and RCS can enhance the accuracy of passive RFID systems in indoor environments, achieving up to 90.3%–100.0% accuracy in experimental setups. These techniques mitigate the impact of environmental signal variations without relying on additional reference tags, making them more practical for dynamic construction site environments. However, despite these advancements, RSSI-based methods remain sensitive to factors such as multipath interference, signal attenuation, and the density of obstacles, which can still affect accuracy in complex environments. Additionally, integrating these methods into real-world construction workflows may require significant customization and calibration efforts to address site-specific challenges.

2.3.4. Visual markers

Smart devices (such as smartphones or smart tablets) have developed rapidly in recent years, and many devices have been integrated with AR technology. Because of this, many systems and experts began to explore AR technology as a method of indoor positioning (Lee et al., 2018; Neges et al., 2017). This technology uses a specific image marker (such as a QR Code or a recognizable image) to enable the system to determine the location based on preset parameters. For example, in the assisting system by Lee et al. (2018), a QR code is used as the basis for indoor positioning. Since a QR code can provide a variety of text message capabilities, it can interpret different information through the decoding action, including location.

The advantage of using visual markers is that this method can avoid the installation of signal infrastructure. The installer only needs to stick the markers of the position reference points on the walls or pillars of the construction site; thus, the installation cost is quite low. Similarly, Shewail et al. (2024) proposed a vision-based indoor tracking system that integrates smartphone sensors with computer vision techniques such as the ORB algorithm for feature extraction. Their system demonstrated a 99% accuracy rate within a 7–10 cm error range, even in complex indoor environments, highlighting AR's potential for precise and infrastructure-free indoor navigation. However, the problem with this positioning method is that a new reference source is needed for each certain interval of distance; otherwise, the accumulated error will become larger and larger (Jiang & Subakti, 2023).

On the other hand, during inspections at the construction stage, on-site signal strength is often weak or unreliable. Additionally, signal-based devices such as iBeacon or RFID frequently experience interruptions and interference due to the constant movement of objects and personnel on construction sites. Installing these signal-based systems also incurs additional costs. Considering these challenges, this research chooses visual markers for indoor positioning.

Considering these challenges, this research chooses visual markers for indoor positioning, as they provide a cost-effective and reliable solution that is less susceptible to signal interference and environmental disruptions commonly encountered on construction sites.

Additionally, to explore the integration of BIM with indoor localization technologies and their applications in construction site contexts, the findings of relevant studies are systematically summarized in Table 4. Beyond offering comprehensive engineering information, BIM serves as a pivotal reference framework for digital space, enabling precise alignment between virtual models and the physical environment. This foundational capability positions BIM as a key enabler for positioning in digital environments such as AR and robotics, facilitating accurate spatial alignment and seamless interaction. By enhancing spatial accuracy, BIM supports effective navigation and integration within digitally augmented and autonomous systems in construction scenarios.

For example, in the study by Acharya et al. (2019), BIM provides edge data for alignment and calibration, enabling users to seamlessly align digital models with the physical environment in real-time. This capability is particularly valuable in AR applications, where geometric precision and structural details from BIM ensure augmented visuals accurately correspond to on-site conditions. This integration significantly enhances the usability and reliability of AR-based workflows, making them more effective in practical construction settings.

2.4. Visual Simultaneous Localization and Mapping (VSLAM) for a construction site

Simultaneous Localization and Mapping (SLAM) has been developed in robotics for over 30 years. It is used in vision technologies to obtain visual data from the physical environment. The concept behind SLAM is that a mobile robot can incrementally build a consistent map when placed in an unknown environment. In addition, it can maintain a real sense of a mobile robot's location (Thrun, 2007). SLAM usually comprises several sensors and algorithms, and by using SLAM, a mobile device (such as a robot, wearable device, smart glasses, a computer, etc.) can concurrently construct a model of an unknown environment (create a virtual map of the location) and simultaneously determine its location. The mobile device conducts feature evaluation while moving and corrects its position and orientation to build a simultaneous map using its sensor and repeated observation of the environment. SLAM can be applied in all scenarios where an already constructed map is unavailable and one needs to be made (Cadena et al., 2016).

Visual SLAM (VSLAM) is a computer vision technology that determines precise indoor location and positioning. VSLAM technology has many applications in various fields, such as autonomous exploration systems, XR (Mixed

Table 3. Comparison of common indoor positioning technologies used on construction sites

Technology	Accuracy	Cost	Benefits	Limitations
iBeacon	Moderate to low	High	Easy to embed in a mobile device, low energy consumption	Limited signal distance, easily affected by environment, demand on extensive coverage
UWB	Very high (cm)	High	Strong penetrability and extensive coverage of signals	Affected by equipment and personnel on site, hard to embed in a mobile device
RFID	Moderate to high (dm-m)	Low to moderate	Lower deployment cost and higher stability	Easily affected by indoor objects
Visual Markers	Moderate (cm)	Low	Easy to install with high accuracy and low cost	Workable only at appointed spots (does not work in real-time), affected by environmental light and background status

Table 4. BIM-integrated indoor localization technologies in construction

Reference	Indoor Positioning Technology	BIM support
Acharya et al. (2019)	VSLAM	BIM provides edge data for alignment and calibration, enabling drift-free indoor localization and AR support. After the initial positioning, achieved by manually selecting three points in the image and matching them with corresponding points in the BIM model, the 3D model's edges are projected onto the image plane and matched with structural edges in the image to establish correspondences between the virtual model and the real-world view.
Liu et al. (2020)	VSLAM & BLE	BIM Provides a 3D model as a calibration reference for defect detection on construction sites. After BLE identifies the user's location, the system aligns the AR model by comparing real-time environmental features with point cloud data. Initially, users manually adjust a BIM component to its real-world equivalent, allowing the system to calculate offsets and align the entire model accurately. SLAM ensures the AR-BIM model stays aligned with the real world as the user moves.
Park et al. (2016)	UWB	BIM provides a detailed navigation map for accurate robot positioning and path planning in construction sites. Initial localization is achieved by aligning the robot's starting point with the BIM model using a total station. The system integrates UWB and motion sensor data to guide the robot along the BIM-planned path.
Mohanty et al. (2020)	BLE	BIM provides spatial data and mapped floor plans to serve as a reference for tracking workers and equipment on construction sites. Initial localization is achieved by BLE tags, the location data is then synchronized with BIM models and displayed on the maps, enabling real-time tracking.
Zhao and Cheah (2023)	Computer Vision (CV)	BIM provides semantic and geometric information of building components for alignment and calibration, enabling autonomous and infrastructure-free indoor localization for robots. The initial positioning achieved by detecting architectural features such as doors, lifts, and staircases and matching them with their corresponding elements in the BIM model, the detected features are further associated with BIM data using relative spatial relationships.
This research	VSLAM & Visual Marker	BIM provides spatial and semantic data for calibration, enabling accurate defect detection and navigation. Initial localization is achieved by scanning visual markers and aligning them with the AR-BIM model. VSLAM detects horizontal and vertical planes to adjust the AR-BIM model in real time, ensuring precise alignment with the physical site and maintaining accuracy during user movement.

Reality) technology, and the AEC industry, as shown in Table 5. Many researchers have delved into how BIM-tracking utilizes the VSLAM method based on a 3D model that uses the device-tracking approach to indoor localization. Recent advancements in VSLAM methodologies have focused on enhancing its performance in dynamic environments through probabilistic, visual, and deep learning techniques. For example, Bouhamatou and Abdessemed (2024) highlight how VSLAM has evolved to address challenges in fields such as medical surgery and precision agriculture, leveraging deep learning algorithms to improve the robustness and accuracy of visual localization and mapping processes. These advancements in diverse, high-stakes environments underscore VSLAM's potential to meet the unique challenges of construction sites, where dynamic conditions, frequent object movement, and complex spatial layouts demand robust and adaptive localization solutions. Their study demonstrates VSLAM's effectiveness in addressing complex environmental challenges, highlighting its potential to improve indoor positioning accuracy and defect tracking efficiency in construction site inspections.

BIM-tracking is based on matching images a mobile device captures with the corresponding BIM view, enabling AR and an Autonomous Navigation System (ANS) to track and fix localization errors. Furthermore, some research has applied the features of VSLAM as a method for indoor positioning. For example, Tseng et al. (2022) reported that VSLAM-based methods are economical and convenient for deployments that mainly use image data without sensor installation. Thus, they presented an indoor localization system based on VSLAM and described it as having high accuracy and low device requirements.

For these reasons, to ensure the stability of BIM modeling tracking and the continuous positioning of inspectors in motion, this study implements VSLAM in the inspection system to reduce errors in the AR calculations. It uses BIM and AR with VSLAM as the indoor positioning method.

Generally, VSLAM inevitably produces observation errors during the calculation process, causing a loss of camera tracking and trajectory drift (Herbers & König, 2019). Hence, some researchers have been working on minimizing the cumulative error. Herbers and König (2019) reported that a device's internal accelerometer could help identify a rotational pitch and roll to match the ground. Acharya et al. (2019) presented an accurate VSLAM and robust visual indoor localization method using a BIM model. They matched the edges in an image to the edges derived from the BIM model to estimate the camera's location in the BIM coordinate system; however, the main limitation was the inability to recover the camera pose after a complete loss of tracking. The results of these studies indicate that a localization accuracy of two meters can be achieved. This paper provides a method to calibrate the X-dimension, Y-dimension, Z-dimension, and yaw values based on the above-reviewed literature.

Table 5. SLAM applications

Topic	Description	Reference
Mobile robot/UAV/vehicle	Using a mobile robot/UAV/vehicle to build a map in an unknown environment and using the map to navigate the environment.	Walker et al. (2019), Liu et al. (2021), Krul et al. (2021)
Indoor localization	Approach to the problem of mobile indoor positioning with a 3D model.	Sydora and Stroulia (2018), Herbers and König (2019), Cadena et al. (2016)
Onsite platforms	System development with a SLAM strategy to support the task of engineers for construction and maintenance.	Liu et al. (2020), Chuang and Sung (2020)
Game development	AR with the SLAM algorithm can improve the user game experience.	Herrera et al. (2019), Bang et al. (2017)

2.5. Summary

The literature review shows that BIM can provide a 3D model to perform model-based visual tracking. As shown in Figure 2, a BIM model provides information about a building, such as the properties of each building element, semantic information, and geometric information. VSLAM features can be used to measure the space, which could make model tracking more accurate by using AR, thereby decreasing model translation and rotation error. Moreover, AR is a visualization tool for mapping the BIM and VSLAM that allows the user to quickly compare the plan with the reality of a construction site to identify differences and thus prevent errors efficiently and intuitively. Therefore, the model-based tracking approach to indoor positioning proposed in this research utilizes the space information of the BIM model and VSLAM.

In addition, the system prototyped in this research aims to achieve the following primary requirements:

1. It enables inspectors to fill in the required information smoothly during operation by providing a friendly UI (Graphical User Interface). In addition, different inspection information can be collected at the construction site and stored in the system database, including photographs (the device's camera must capture the images), text, construction site information, inspection forms, and location information.
2. It enables an inspector to compare the actual construction site and the BIM model to identify any differences by using AR to visualize the information in the system. In addition, by applying the BIM model, the position of the inspector on the construction site can also be accurately recorded for subsequent viewing and utilization.
3. It ensures that inspectors can move to defects while overlaying an AR-BIM model using AR and that the model continues to fit the real environment using VSLAM technology. Furthermore, the system must provide the user with a simple model calibration function to ensure the model's position during movement is calibrated in real time.
4. It can record locations within a construction site. The inspector can record the location when recording the defective items. The location information can be quickly found during subsequent discussions and repairs to reduce human error.

3. Mechanism of integrating BIM and AR with VSLAM

3.1. Application pipeline of BIM and AR with VSLAM

The proposed BIM-based quality inspection system integrates BIM and AR with VSLAM techniques as its core, enabling precise calibration between the BIM model and the real site. Figure 3 illustrates the integration of these techniques in the design, which can be divided into three components. The first component extracts the geometry

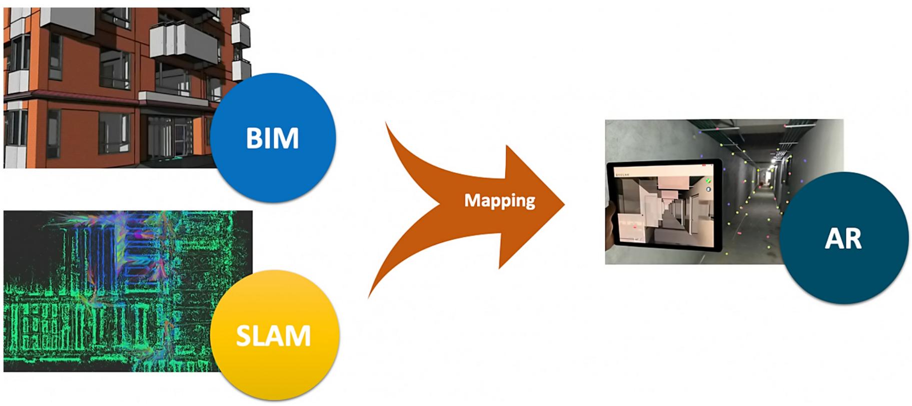

Figure 2. The roles of BIM, VSLAM, and AR in the proposed system

and non-geometry data from the BIM Model. The second component is AR pre-processing: this study set up an AR environment before using the AR function in the system. This component describes the three steps needed to complete AR pre-processing. The third component is AR with VSLAM: this component describes how the system overlays the AR-BIM model onto physical space and locates the indoor position.

3.1.1. BIM Information extraction

The BIM information extraction component aims to provide building information for construction inspection. First, this study created a BIM model using Revit, which allows the user to create digital twins for different disciplines (HVAC, fire, structural, etc.) in various data formats (such as DXF™, DGN, and IFC). After creating the BIM Model, this study converted the geometric information and non-geometric data into the specific format for Xcode, Apple's integrated development environment (IDE), for use with AR. Specifically, the Revit model (.rvt) was exported to an IFC file, an open format used by BIM programs. Then, the geometric and non-geometric information of the IFC file was converted through the program developed in this research. The outputs are lightweight files, including one Dae file and one JSON file with geometric and non-geometric information, respectively (please see Section 4.1.2 for details).

3.1.2. AR Pre-Processing

Pre-processing for the BIM models is necessary to inspect defect items by comparing the model to the construction site via AR. This research integrated AR with a mobile application using ARKit. ARKit is Apple's augmented reality development framework, released in June 2017, and it is compatible with iOS devices. ARKit allows users to use AR functions intuitively, and the ARKit framework is built into smart devices through Xcode. The pre-processing includes three steps: (1) export into a geometry viewer, (2) set position, and (3) tag mapping.

Step 1: Export into a geometry viewer

The Revit file is converted into the .dae format compatible with Xcode to integrate the model into the AR environment. Figure 4 shows the geometry view in Xcode. Next, a 3D model is added as an AR resource (.dae file). This step imported geometry and coordinate information into the AR environment. Then, this information can be used to correspond with the location space set in actual use.

Step 2: Set the position

In this step, the checkpoint on every floor in the building is set for indoor positioning. For example, the checkpoint set on the first floor is named "AR1F-Tag-A" (Figure 5). By scanning tags like "AR1F-Tag-A", the smart device can establish the user's current position and generate a corresponding AR-BIM model of that location, improving navigation or assisting with other location-based services.

Step 3: Tag mapping

Since ARkit provides image recognition, different graphic tags are created and mapped to the checkpoints individually. For instance, this research placed the tags (Figure 6) in the real world, and through the API provided by ARKit, the tag'stag's name, "AR1F-Tag-A", is mapped to "ar1fTagNode" (Figure 7). Thus, when a smart device scans the tag, the system can locate the corresponding position in the AR-BIM model.

3.1.3. Visual SLAM/XR

Since ARkit has a VSLAM feature, it allows the user to capture and scan a space immediately. Oufqir et al. (2020) reported four main features of ARkit for processing data delivered by its built-in Inertial Measurement Unit (IMU) sensor. The first feature is tracking, which enables a smartphone to track real-world positions. ARkit uses the Visual Inertial Odometer (VIO), which combines the image data from the camera and the device's motion sensor (Apple Inc., 2017). Generally, AR depends on mechanical world tracking to track the position in a real environment, which relies on computing motion sensor data (such as acceleration sensors and gyroscopes) to track the movement of the smart device; however, this method is prone to high-speed movement errors (such as drift conditions). Thus, computer vision (CV) technology calculates each picture frame. As a result, the direction of movement can be calculated with better accuracy. However, this method will still lengthen the system's calculation time; therefore, ARkit integrates the advantages of these two methods. The interactive calculation of these two methods improves the logic of world tracking, increases accuracy, and provides more sensitive result calculations when moving at high speeds.

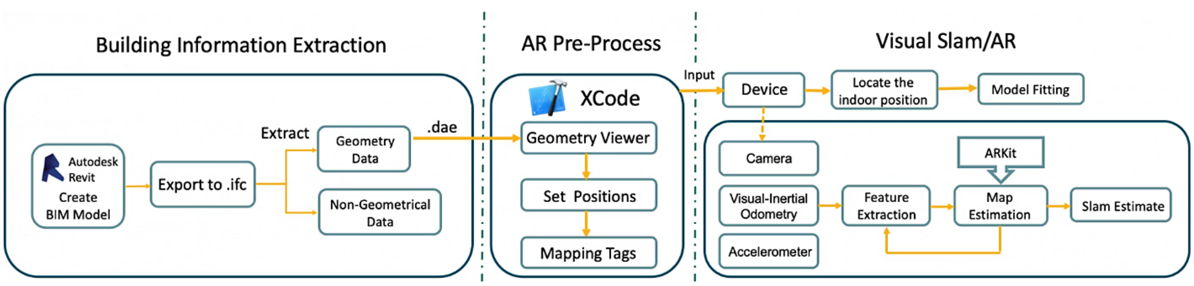

Figure 3. The application pipeline of BIM and AR with VSLAM

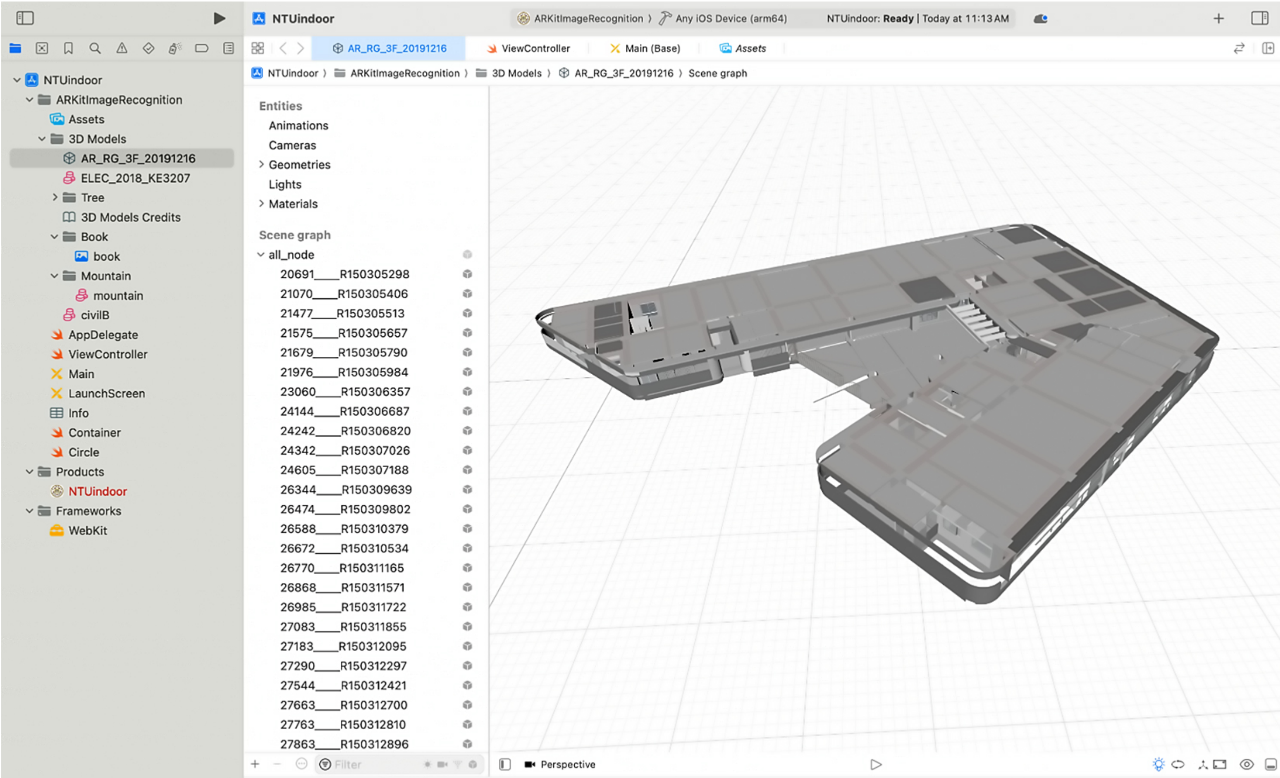

Figure 4. Geometry viewer in Xcode

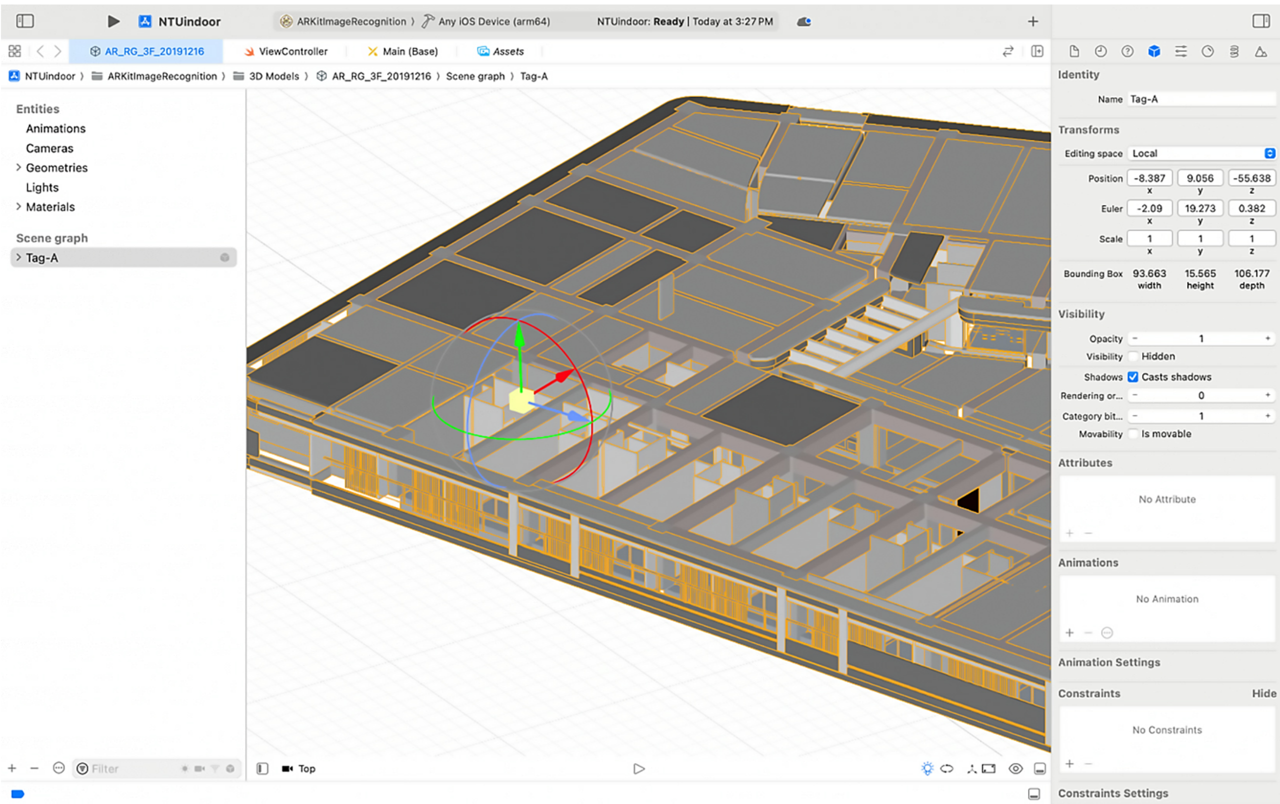

Figure 5. Checkpoints are added to every floor for indoor positioning

Figure 6. Tag picture-A1F

```
func getNode(withImageName name: String) -> SCNNode
{
        var node = SCNNode()
        switch name {
        case "AR1F-Tag-A":
            node = ar1fTagANode()
        case "AR1F-Tag-B":
            node = ar1fTagBNode()
        case "AR1F-Tag-C":
            node = ar1fTagCNode()
        case "AR2F-Tag-A":
            node = ar2fTagANode()
        case "AR2F-Tag-B":
            node = ar2fTagBNode()
        case "AR2F-Tag-C"
            node = ar2fTagCNode()
        default:

        break
       }
```

Figure 7. Mapping between picture and node

The second feature is an understanding of an unknown environment. ARkit helps smart devices (iPhone, iPad, etc.) recognize an unknown environment. ARKit uses the device's camera and motion sensors to capture and track the position and orientation of the device in 3D space. It then creates a point cloud representation of the environment. Next, it derives spatial features from the point cloud data, including objects' size, shape, orientation, and real-world vertical and horizontal flat surfaces. The third feature is 2D image recognition. With ARkit, smart devices can recognize a 2D image stored in the application and display or project virtual information onto the image. The last feature involves using the brightness sensor to determine the amount of light in a surrounding room to apply a degree of brightness to a virtual object.

Figure 8 illustrates the mechanism of integrating BIM and AR in the BIM-based Quality Inspection System prototyped in this research. ARFrame, an API provided by ARKit, retrieves image data capturing the scene from the camera and utilizes CV algorithms to analyze the image data and detect and track feature points, such as edges and corners. In addition, it retrieves motion data from sensors (such as accelerometers and gyroscopes) to determine the device's position and movement. To ensure the consistency between AR-BIM and the real environment and to record the user'suser's indoor position, the indoor positioning module, developed using VSLAM technology in this research, enables users to record their indoor position in real time during the inspection process. The system in this research used the image recognition feature of ARkit to scan the tag images (checkpoint), as shown in Figure 9. After detecting the tag image, the system immediately projects the AR-BIM model with the corresponding position on the screen (Figure 10). The system continuously updates the device position according to the VIO data and computer vision to make AR-BIM models align geometri-

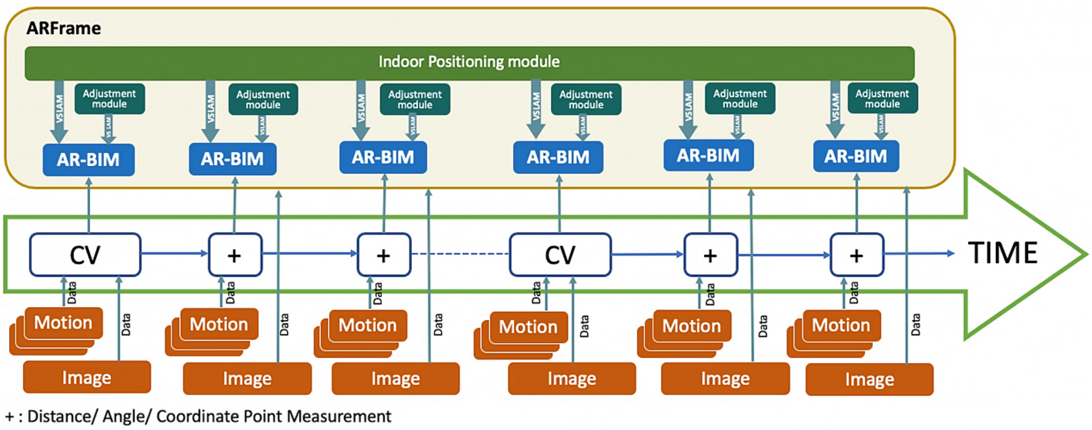

Figure 8. The mechanism of integrating BIM and AR in the BIM-based Quality Inspection System

Figure 9. Scan tag image used to determine the location

Figure 10. Continual updating of the coordinate position

cally with the physical environment. However, the model onscreen usually does not fit the onscreen real environment well. Therefore, the adjustment module developed in this research assists the AR-BIM model in maintaining the right track. As a result, the system maintains the position after the user moves the camera.

3.2. Calibrating positions of AR-BIM via VSLAM

Using VSLAM, the computer vision method can create a map of the environment simultaneously with the operation of the visual-inertial odometer. This method creates point cloud data of the unknown environment through Structure from Motion (SfM). The cloud data can also position and correct the AR-BIM model (Hsieh et al., 2023). For instance, when the spatial feature appears in the point cloud, these points are coplanar in three-dimensional space and can be recognized as a plane (Figure 11).

This research utilizes the horizontal plane detected on a construction site to correct the Y-direction positioning in the AR-BIM model. The horizontal plane, often identified through LiDAR sensors, serves as a reference for accurate alignment between the physical environment and the digital model. After the horizontal plane is detected using LiDAR, the corresponding height (i.e., y = 0) in the AR-BIM model is mapped directly to this physical plane. This ensures that the AR model's representation aligns precisely with the actual construction site, eliminating vertical discrepancies that may arise due to errors in positioning.

By referencing this detected plane, the system can adjust the Y-coordinate of the model, ensuring that all elements in the AR-BIM model are aligned with the actual site's geometry, as depicted in Figure 12.

The AR-BIM model's x-direction, z-direction, and yaw values must also be corrected. Figure 13 illustrates the steps of model position correction. The blue line indicates a column in the space, the orange line indicates the column in the AR-BIM model, and the red line indicates surface detection. The x-direction and y-direction have error distances between the column and the model. At first, the system will detect a vertical plane (such as a wall or column), then calculate the distance between the column and the model and offset the model to the same face. Next, the system will offset the other face of the model to align with the column. Following these steps, the AR-BIM model will align with the real object.

As shown in Figure 13 (Step 1), first, the user needs to scan the tag picture placed in a construction site to map the position with an AR-BIM model while the AR-BIM model projects onscreen. Then, the user needs to detect the ground plane using the device camera (shown in Figure 13 (Step 2)) to correct the AR-BIM model's y-position and fix the floor of the BIM model. Finally, the user must correct the orientation of the AR-BIM model by using the camera to detect a vertical plane (such as a wall or column), as shown in Figure 13 (Step 3). After these steps, the user can move to the construction site. The system detects the planes simultaneously to achieve real-time correction of the AR-BIM model position (Figure 13 (Step 4)).

Figure 11. SLAM detects a horizontal plane

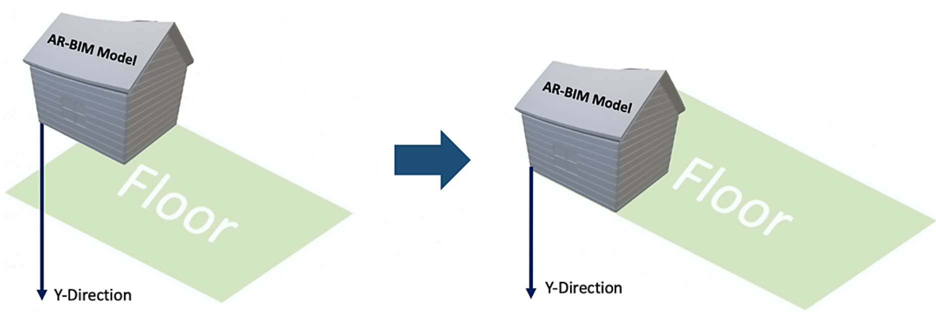

Figure 12. Position correction of a BIM model (Y-Direction)

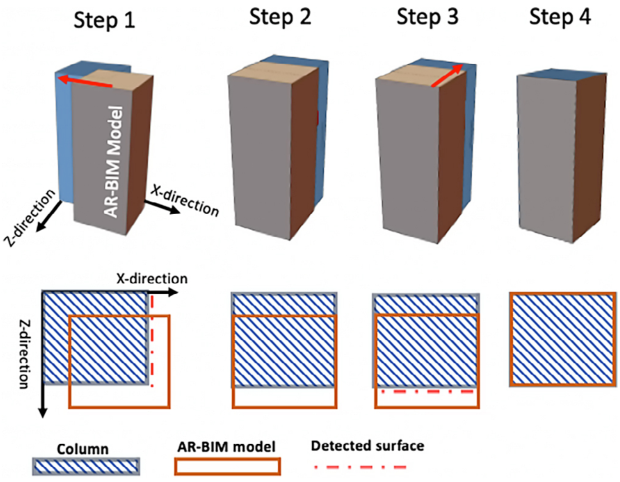

Figure 13. Steps of model position correction

4. System implementation

This section describes the proposed data preparation process and indoor location positioning method in more detail. The experiments are described in Section 5.

5.1. System framework

The proposed system provides indoor location positioning and quality issue marking. Figure 14 illustrates the proposed system framework, consisting of five modules: BIM, database, indoor positioning module, adjustment module, and Mobile application. The BIM models provide the system with geometric and textual information (such as element properties) about buildings from different phases. The database includes four major construction site inspection information: (1) self-check, (2) Hygiene Audit (HS) checklist, (3) Quality Audit (QA) checklist, and (4) BIM data. The indoor positioning module gives users the position inside a building determined using AR. This paper implemented the module through ARkit in the iOS development environment. To ensure the projected 3D model maintains the correct overlay on real objects, an adjustment module was implemented to correct the model position continually. The visualization module provides an easy-to-use GUI for users to operate, presenting detailed information about the inspection project and the BIM model information. Users can view the BIM model through AR and present the inspection form. Finally, to record the defective items on the construction site, the system can assist the inspector in collecting information on defective construction items (such as pictures, defect position, etc.). This research integrates all five modules to develop a BIM-based quality inspection system to assist inspectors in checking construction site items conveniently and efficiently.

4.1.1. Database

The database module is an essential component of the system implemented in the system's server (as shown in Figure 14). The inspection system contains three inspection forms to collect construction site inspection information on a construction site, including internal audit, safety and hygiene audit, and quality audit:

1. Internal audit: A construction company must audit construction items internally before all other formal inspections. That is, this schema will store the information about construction defect items, including information about the construction company, inspector, inspection date, etc.
2. Hygiene and Safety Audit (HS): a Hygiene and Safety Audit expert assesses a construction site's health and safety policies.
3. Quality Audit (QA): stores Quality Audit information to reduce defects and enhance product quality.

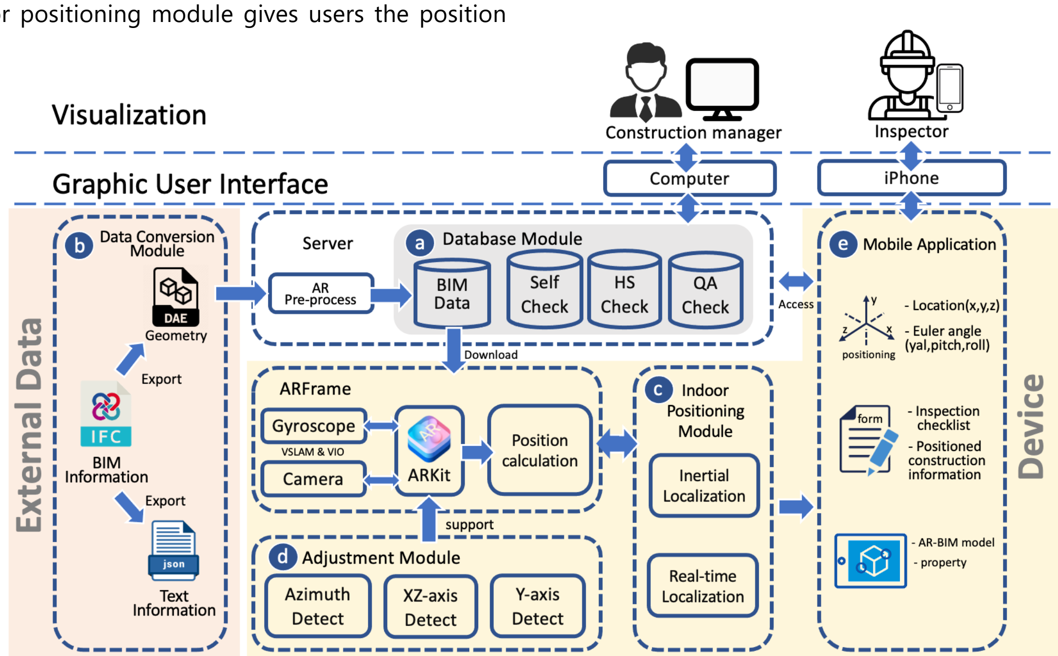

Figure 14. Overview of the system framework: a – database module; b – data conversion module; c – indoor positioning module; d – adjustment module; e – mobile application

Each form has a scheme with the quality issue, element, position, picture, and time information. For instance, during a quality inspection, the system generates an inspection form for the inspector to fill out on the interface. Once completed, the form data and accompanying photos are stored in the database. In addition, the photos are tagged with position information, allowing subsequent inspectors to access and refer them easily.

4.1.2. Data conversion module

To cope with the harsh conditions of a construction site with weak or no signal, the system first downloads the AR-BIM model into a mobile device before the inspection. Because site network signals are often unstable or weak, this study suggests downloading the model to a mobile device in the .dae format before the site inspection/audit to view the model without requiring access to a network. Furthermore, since the .dae model does not contain construction information, non-geometric data (JSON) should be imported into the system so that the geometric and non-geometric information of the model components can be mapped onto it. This study proposes the development of a conversion module to assist in reducing file size and optimizing the system's performance. As shown in Figure 15, a conversion module is designed to convert IFC (.ifc) files into the model file format (DAE) and data file format (JSON). The conversion module utilizes the IfcOpenShell open-source software library to convert the .ifc file format to the .dae format. The .dae format features a clear data structure and relatively small file size, allowing for efficient storage and browsing on a device. Also, the module converts the IFC file format to the JSON file format using the XBIM toolkit to reduce the space required for data transmission and storage. The BIM model in the case study of this work was exported from the Revit file (47.7 Mb) to the DAE file and the JSON file, and the resulting file sizes are 10.2 Mb and 12.0 Mb, respectively.

Data processing

The geometric information of the BIM model is extracted for on-site inspection. First, the BIM model must be exported to the .ifc format. Figure 16 demonstrates exporting the BIM model from Revit to the .ifc format. This study discovered that the ID parameter included in the .dae format is necessary for extracting element properties from IFC models and their storage in files of text-based format such as JSON files) for mapping the parameter properties of model objects. Therefore, the inspector can access the element parameters using the ID information, as the system effectively maps the ID to the corresponding parameters in the JSON file. For this reason, this research developed a conversion tool capable of translating the .ifc to both the .dae and the .json file formats (Figure 17).

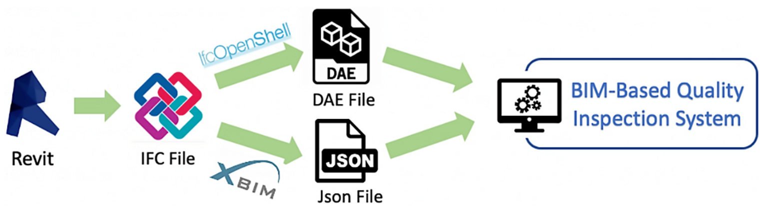

Figure 15. BIM data processing

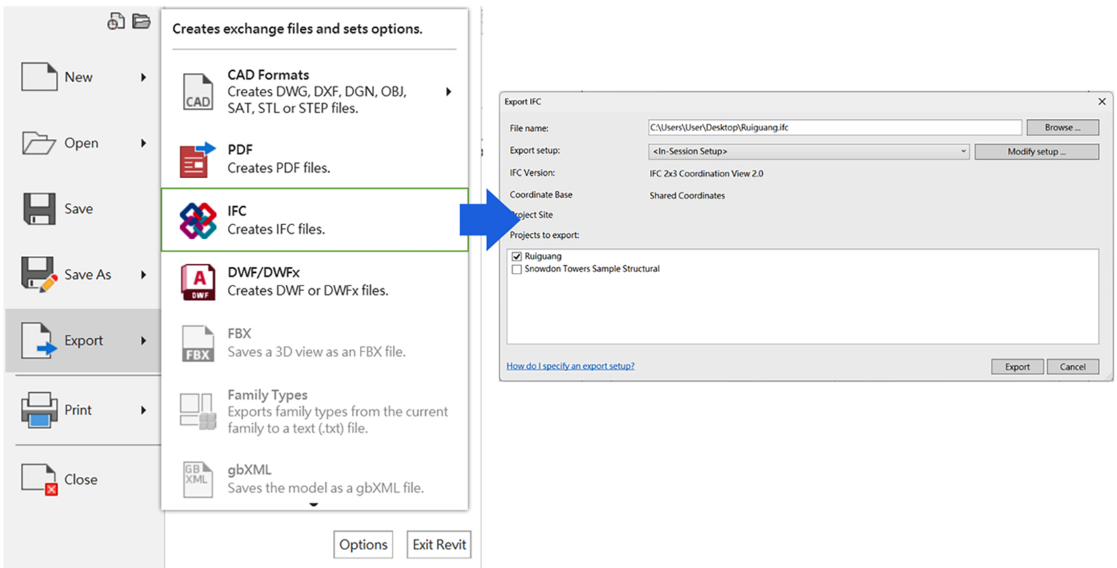

Figure 16. Export to IFC file from Revit

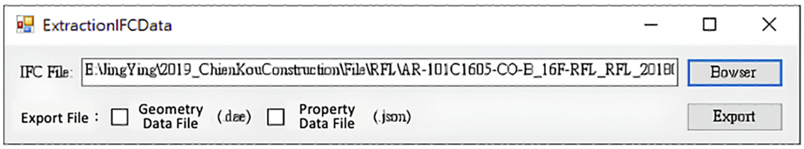

Figure 17. Extraction of IFC data

4.1.3. Indoor positioning module

This research uses ARkit to project the AR-BIM model onto the construction site. ARkit has three critical layers: tracking, scene understanding, and rendering. Tracking is the most basic function of the AR technique: creating and tracking correspondence between the user's real environment and a virtual object. The tracking process combines a device's motion-sensing hardware with computer vision to calculate the device's location and orientation; thus, the tracking system continuously projects the virtual object onto the correct location. The scene understanding layer enables the ARkit to recognize the environment through the camera view to detect horizontal and vertical planes. This obtains the position where the virtual object is to be placed. Lastly, the rendering layer plays an important role in displaying the 3D model in the camera view, relating to its material, geometry, and light properties. Based on the features of ARKit mentioned above, this study proposes a hybrid indoor positioning approach that includes initial localization and real-time localization (please see Section 5.2 for details).

4.1.4. Adjustment module

The adjustment module is the most crucial part of the system. For example, when an inspector scans a label using the camera view of a device on a construction site, the system registers the 3D BIM model in the device; however, the camera cannot always detect the appropriate label when the inspector walks around the construction site. The image detection module of ARkit does not work when the camera view does not detect the label, which serves as an anchor. Instead, location errors of the AR-BIM model may occur, including X, Y, and Z-direction and azimuth errors when AR is used during movement. Thus, this research proposes a method that combines computer vision with a physical engine to adjust for these errors when they occur (please refer to Section 3.2) based on the VSLAM technique.

4.1.5. Mobile application

The Mobile application lets the user operate the system easily through a smart device and quickly check information related to construction defect items. This research prototypes the system in an iOS environment, with a graphical user interface to connect with the database to perform various operations, such as indoor position, quality defect issues management, picture editing, and interaction with the AR-BIM model.

4.2. BPMN of the system workflow

This section presents the system workflow using the Construction Inspect System's Business Process Model and Notation (BPMN) (OMG, 2011). BPMN is a visual modeling language for business analysis applications used to specify enterprise process workflow, employing a standard notation that is readily understandable to all business stakeholders. This section is divided into two stages to explain the system process: on-site inspection pre-processing and on-site inspection.

4.2.1. On-site inspection pre-processing

Before using the system to inspect the defective construction item, the construction manager must set up the BIM model and files, including processing BIM model files and setting model checkpoints. So, there are four lanes in the BPMN diagram for the pre-processing inspection stage (shown in Figure 18): (1) Construction manager, (2) Server, (3) Server (Database), and (4) Device. The major events in Figure 18 are explained as follows:

a. Create BIM Model

The construction manager must create a 1:1 BIM model using BIM software (Revit). Subsequently, it is necessary to export the file in .ifc format due to the need for conversion. Also, to conduct on-site inspections, the user must install the application developed by this research on the device beforehand.

b. Converting File

Convert the .ifc format to .dae and .json format through the conversion tool.

c. Import .dae into Xcode

The AR pre-process must be completed to ensure the model can be used in AR.

4.2.2. On-site inspection

The system's operation for construction site inspection is divided into two stages: task generation and on-site inspection. Before the site inspection is conducted, the task generation phase must be completed. During this phase, the user must download the site inspection information, such as defective item data and AR-BIM models, onto the device. These downloaded resources are then used for the subsequent on-site inspections. There are four lanes in the BPMN diagram for the proposed construction inspection system approach (shown in Figure 19): (1) User, (2) Construction Inspection System, (3) Local Device (Database), and (4) Server (Database). The User Lane includes inspec-

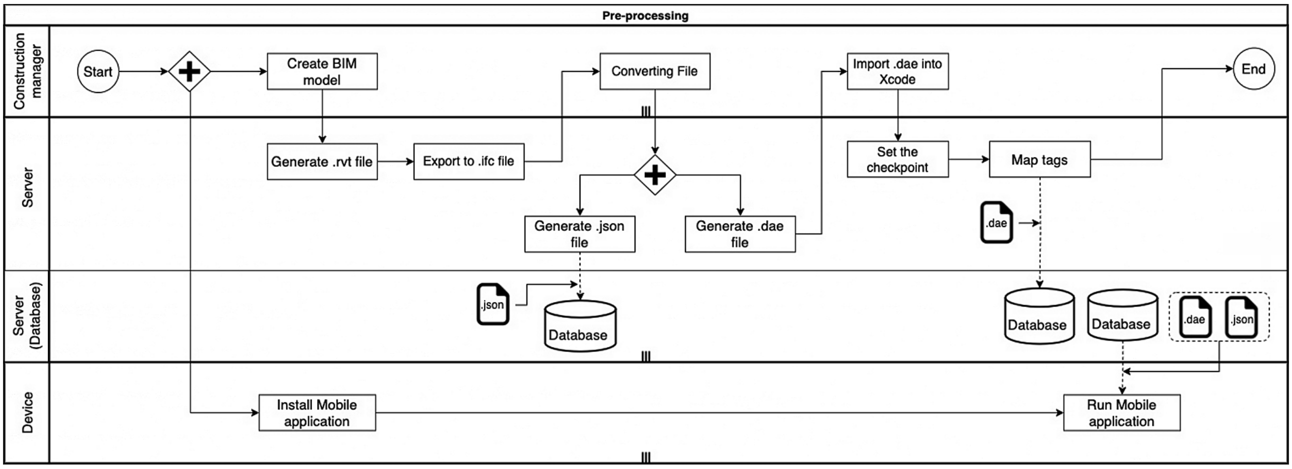

Figure 18. The business process of on-site inspection pre-processing

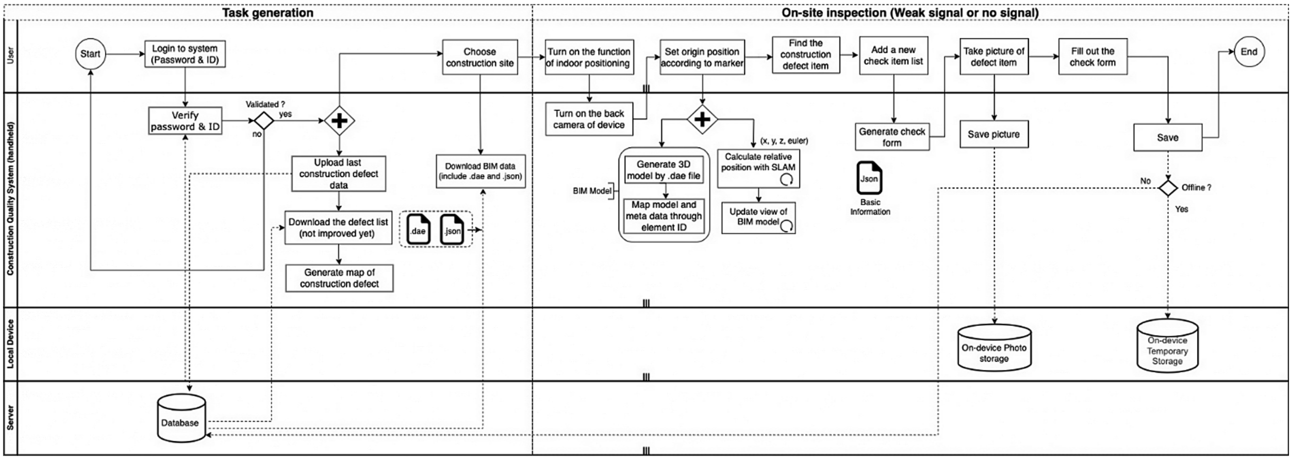

Figure 19. The business process of the proposed system

tors of construction sites or managers. The Construction Inspection System Lane refers to the system developed in this research. Finally, the databases are implemented in the Local Device (Database) Lane and Server (Database).

a. System login

When a user logs in to the system, it asks for and verifies their user ID and password. Users can choose the construction site they want to access if the account is successfully verified.

b. Choose a construction site

After the user logs in to the system, the system shows a list of construction sites from which they can choose. Meanwhile, the system will upload the inspection records to the database if they have not been uploaded yet.

c. Turn on the indoor positioning function

The SLAM positioning technology is adopted for this function. First, the user scans the tag placed on the site. Then, after comparing the features, the system locates the starting position of the device in space and obtains the user's motion path through the space using the SLAM algorithm. At the same time, the perspective within the model (AR-BIM) is updated to the user's relative position.

d. Perform inspection

When users spot a defect, they can create an inspection item and access site information from the database.

e. Take a picture of the defective item

The system stores the photo in the device and records the defective item information, such as the photoshoot's location, basic information about the item, etc.

f. Save

After completing all previous actions, users can click the save button to archive the inspected data in the device or the backend database.

5. System validation at a construction site

This section demonstrates how the BIM-based quality inspection system is utilized on actual construction sites. It uses AR to present a BIM model, which allows inspectors to check construction site elements and collect defect item information efficiently. In addition, the system records the inspector's location in the BIM model; thus, the user can mark the location of each defective item.

5.1. Case description

This study prototyped a BIM-based quality inspection system with an engineering company. A case study was conducted at a Taipei construction site, Ruiguang Social Housing (Figure 20). The building is an RC structure with 14 stories and four basement levels. Since it is a residential building, there are more structural repetitions. The experiment was conducted on the second floor because its construction was almost completed (see Figure 21).

5.2. Test results

The hybrid approach integrated the visual marker method deployed on walls for initial localization and VSLAM for real-time positioning. As shown in Figure 22, the system needs first to scan a marker to determine the initial location on a construction site. Then, the horizontal plane (such as the floor) needs to be detected to calibrate the height of the AR-BIM model. After scanning the marker, the device showed the user's corresponding position in the AR-BIM model. The device must keep the camera on during user movement until the information on the defective item has been recorded. A video demonstration of this process is provided at https://www.youtube.com/watch?v=yJQzamk7C_M&ab_channel=NTUBIMCenter.

After the user moves 20 meters, the AR-BIM model overlays the physical environment (Figure 23). To verify the accuracy of the Visual Odometry, this study recorded the path of the movement. According to the route line shown in Figure 24, it can be observed that when the model is shifted, the adjustment module is immediately triggered and corrects the offset; however, it is difficult to figure out the distance error when the environmental factors (such as luminance and material) vary dynamically at a construction site. Therefore, this study suggests that the environment be kept bright during this process.

The adjustment module can ensure that the model does not significantly shift due to the movement of the inspector and that the model is moved to the correct position on time. When the user finds that the model is offset, the model can be moved back to the vertical plane detected by the device's camera. For example, when an inspector finds a positional difference between a beam in the model and real space, the inspector can click the red spot, a vertical face detected by the camera (Figure 25), to signal the system to adjust the model to the correct position.

Figure 26 shows the overlay of the BIM model on the images of the construction site using AR. These frames'frames' location and rotational errors vary from 0.1–0.25 meters and 1°–1.53°, respectively. This shows the level of accuracy that can be achieved when integrating BIM with AR, highlighting some of the minor discrepancies in positioning and rotation within the construction site. These errors are generally within an acceptable range for real-time AR applications, but efforts can still be made to minimize these inaccuracies for improved precision.

Figure 20. Ruiguang social housing

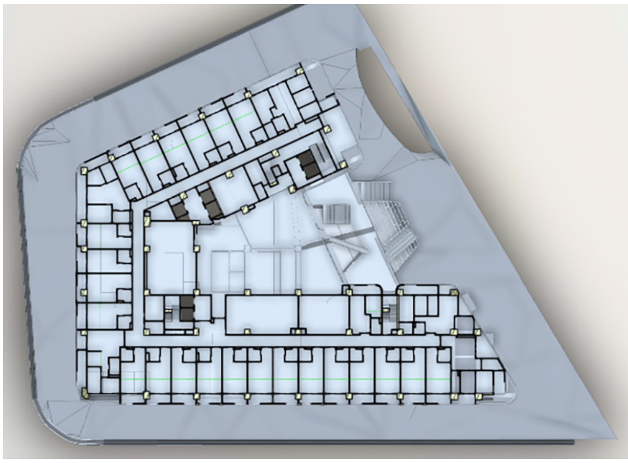

Figure 21. The second floor of the construction site

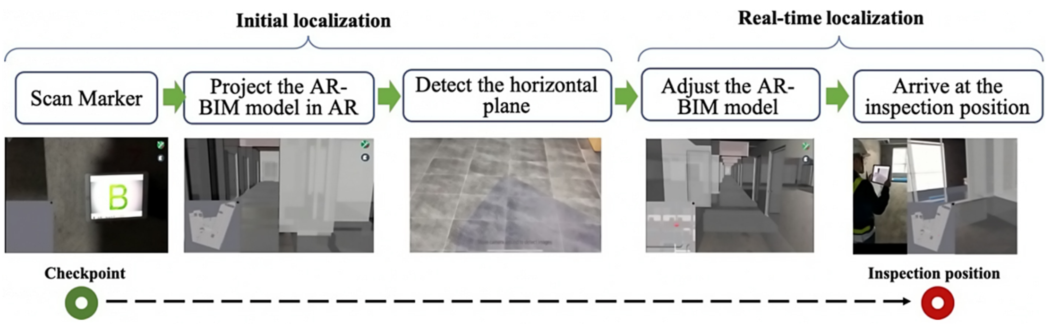

Figure 22. Indoor positioning at the construction site

Figure 23. The BIM model overlying a scene

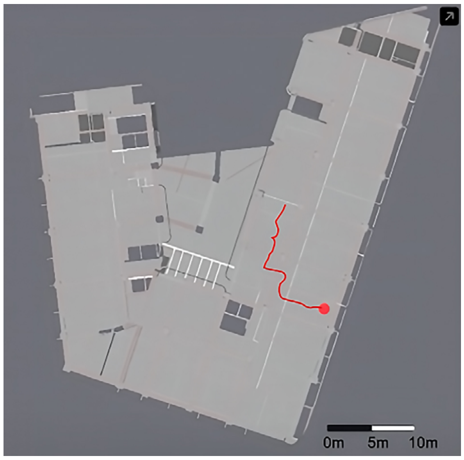

Figure 24. The movement path

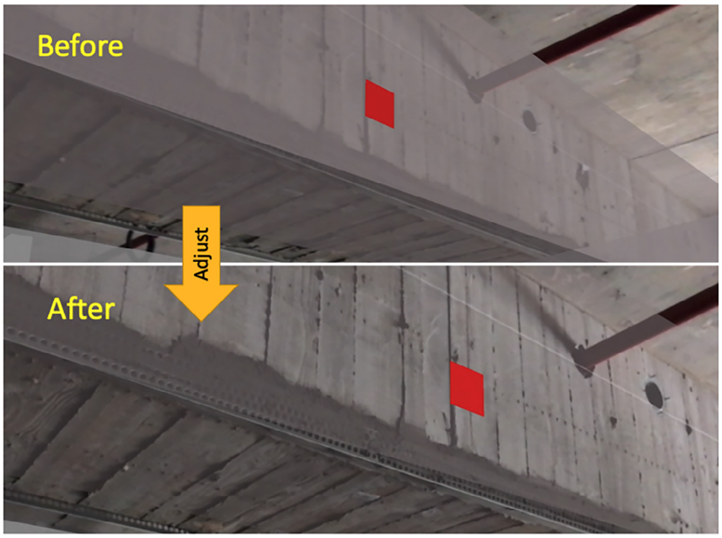

Figure 25. Adjustment of the model position

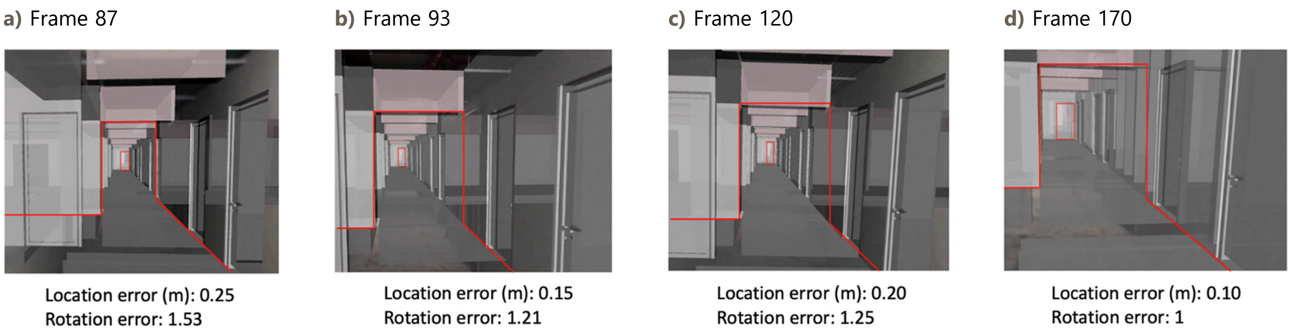

Figure 26. Location error and rotation error of four selected test images by the device's camera

5.2.1. Construction defect item list

This system provides a straightforward interface for inspectors to check defect items, and it lists and shows the defect item information that needs improvement (as shown in Figure 27). For example, the information includes the position of the construction defect item, item name, picture, creator name, and repair date. In addition, an inspector can add a new form when they find an error onsite (as shown in Figure 28), and the system provides different forms, such as a Quality Audit (QA) check form, Hygiene and Safety Audit (HS) check form, and a defect item check form.

5.2.2. Map of the construction defect items

Inspectors may not be familiar with the environment on a large-scale construction site. Thus, this system provides a map for marking the position of defective items (Figure 29). This helps inspectors intuitively grasp the place and content of an item. In addition, the system leverages the BIM model to save the position of a defective item; thus, its location can be immediately displayed when inspectors browse defective items.

5.2.3. Photograph and marking

This function provides an inspector with a simple drawing tool to mark the defective item on the photos immediately after taking them (Figure 30). In addition, the system can overlay the AR-BIM model on a scene for comparison before taking photos to facilitate inspection (Figure 31).

5.3. User feedback summary and recommendations

This study prototyped a BIM-based quality inspection system in collaboration with a leading engineering company in Taiwan. User feedback, collected through interviews, highlighted the system's strengths and areas for improvement. Quality managers and industry professionals praised its ability to enhance defect inspection efficiency by streamlining data collection and enabling seamless backend storage for analysis and reporting. Key features such as defect data mapping, photo annotation, and the AR-BIM function were recognized as valuable tools for managing construction quality.

For the marker-based indoor positioning functionality, users suggested improvements in marker management due to the dynamic nature of construction sites, where pre-placed markers are often displaced or damaged during ongoing activities. This underscores the need for strategies to improve marker durability and placement consistency, which would enhance positioning reliability. While

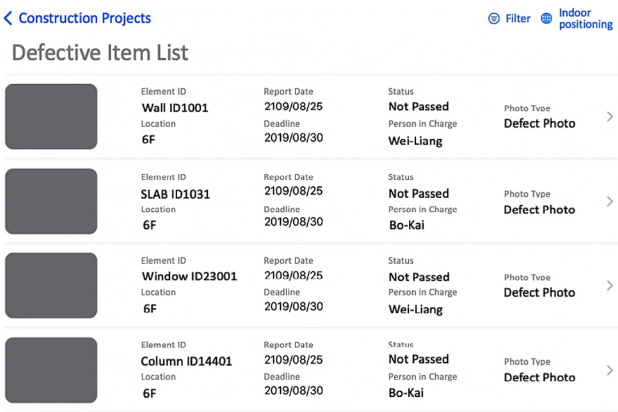

Figure 27. List of forms for a defective item

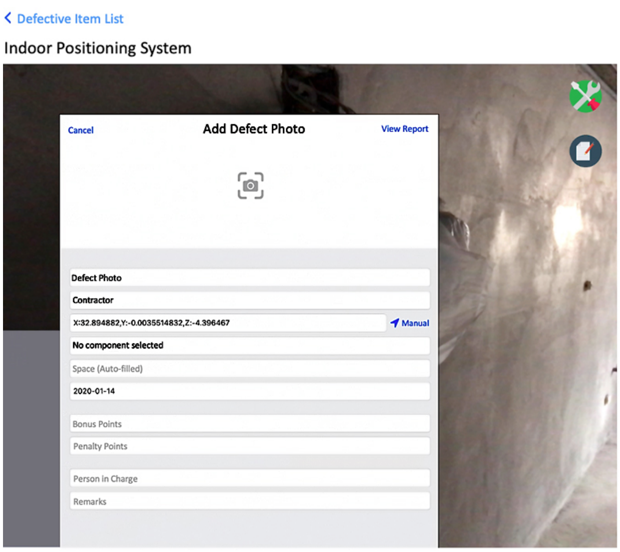

Figure 28. Form to add a new defect item

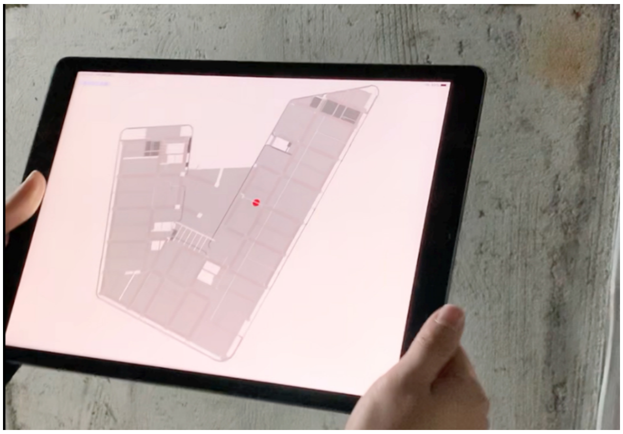

Figure 29. Map showing the location of a defective item

Figure 30. Photograph marked up by an inspector (red circle)

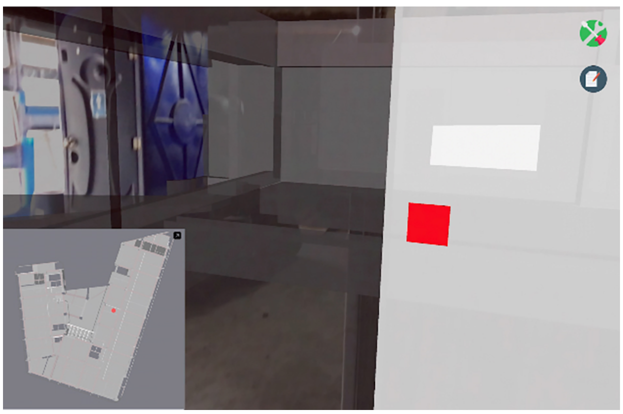

Figure 31. Overlay of the BIM model on the screen

the current implementation is promising, further refinements could significantly improve its practicality and usability on-site. To address marker failures caused by damage or displacement, we developed a manual positioning feature, allowing users to mark positions directly on the map when automated recognition is unavailable.

To further optimize system performance, users recommended exploring more robust positioning technologies, such as VSLAM, to complement marker-based methods and improve accuracy. They also suggested simplifying the interface to create a more intuitive user experience and enhancing offline functionality to ensure stable operation in dynamic site conditions. Regarding the AR-BIM usability, while users appreciated the convenience of automatic model alignment, they found holding devices throughout the inspection process cumbersome. To address this, they proposed exploring wearable solutions, such as head-mounted displays, to improve convenience and efficiency. These enhancements are essential for maximizing the system's practicality and effectiveness in real-world construction environments.

6. Conclusions

To facilitate on-site construction inspection, this research proposes a system framework that uses BIM and AR capabilities with VSLAM to build an AR-BIM-based quality inspection system. In the framework, the BIM model of the construction site contains geometrical elements linked to a database containing all related project information (such as geometric data, material, company information, etc.) for a site inspector to obtain space and element information about the site quickly. Integrating BIM and AR allows the system to map an AR-BIM model to the real world on a construction site, while VSLAM enables an inspector to navigate in a real-world environment and be tracked in the AR-BIM space. To address the issue of indoor positioning in construction sites without network signals and the problem of model offset errors when using AR with VSLAM, this research proposes a hybrid approach that uses the visual marker method for initial localization and then VSLAM with a tracking error adjustment module for accurate real-time positioning. This research uses the proposed framework to implement a prototype system to validate this approach and evaluate its effectiveness and performance on several construction sites. The results indicate that the system is capable of accurate real-time indoor positioning and projection of the BIM model onto the site's AR environment without network signals. Overall, the contributions of this paper are:

1. This study presents the system framework of a construction quality inspection system that aims to provide inspectors with a system that can easily collect information about a construction site. The system integrates BIM and AR with VSLAM to improve the efficiency of the inspection process (defects per unit of inspection time) and reduce the possibility of human errors in recording, especially the location of inspected items. Additionally, this paper describes the process and method of integrating BIM and AR with SLAM to facilitate the implementation of this functionality (see Section 3) into a quality inspection system.
2. This research proposes a hybrid approach that uses the visual marker method deployed on a wall for initial localization and then VSLAM for real-time positioning to perform indoor positioning in an environment with no network signal. As an indoor positioning technique, the visual marker method allows the system to attain localization with good precision in environments even without a network signal. This approach ensures accuracy in initial localization and significant cost-saving benefits during installation. For real-time localization, this study integrates BIM and AR with SLAM to calculate the inspector's spatial trajectory in real-time using the BIM model-based tracking approach. This research introduces an adjustment method that allows the system to continuously calibrate the model's position in AR, ensuring automatic alignment with the physical space to overcome tracking errors in AR. Visual-inertial odometer measurements and positioning correction deviations at a construction site are used to reduce calculation errors. The results demonstrate that the model can still be accurately projected on-site even after moving 20 meters from the initial location.
3. The prototype system developed in this research has been practically implemented and tested on construction sites for quality inspection. With on-site positioning and adjustment modules in the integrated framework of BIM and AR with SLAM, the system allows users to record the inspected results with position information easily. As a result, the willingness of inspectors to use an on-site quality inspection system like the one prototyped in this research is increased.

While the proposed system demonstrates significant improvements in construction site inspections, several limitations were identified during its development and testing. One notable limitation is the system's reliance on the quality of visual marker for accurate positioning. Poorly maintained or improperly placed tags can reduce performance accuracy. In addition, a future direction for this research is to increase automation of the inspection system to recognize construction defect items through image recognition. With enough collected on-site images labeled in the inspection process, deep learning techniques may be applied to train the system for automatic image recognition of construction defects.

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References

Ashour, Z., & Yan, W. (2020). BIM-powered augmented reality for advancing human-building interaction. In *Proceedings of the 38th Conference on Education and Research in Computer-Aided Architectural Design in Europe* (*eCAADe*) (pp. 169–178), Berlin, Germany. https://doi.org/10.52842/conf.ecaade.2020.1.169

Acharya, D., Ramezani, M., Khoshelham, K., & Winter, S. (2019). BIM-Tracker: A model-based visual tracking approach for indoor localisation using a 3D building model. *ISPRS Journal of Photogrammetry and Remote Sensing*, *150*, 157–171. https://doi.org/10.1016/j.isprsjprs.2019.02.014

Adebowale, O. J., & Agumba, J. N. (2022). Applications of augmented reality for construction productivity improvement: A systematic review. *Smart and Sustainable Built Environment*, *13*(3), 479–495. https://doi.org/10.1108/SASBE-06-2022-0128

Alizadehsalehi, S., Hadavi, A., & Huang, J. C. (2020). From BIM to extended reality in AEC industry. *Automation in Construction*, *116*, Article 103254. https://doi.org/10.1016/j.autcon.2020.103254

Achkar, E. (2016). *A BIM-integrated approach to construction quality management. Enabling information and knowledge management during the execution phase of a project life cycle* [Master's thesis]. Eindhoven University of Technology, Netherlands.

Apple Inc. (2017). *Augmented reality*. https://developer.apple.com/videos/play/wwdc2018/610/

Baiburin, A. K. (2017). Errors, defects and safety control at construction stage. *Procedia Engineering*, *206*, 807–813. https://doi.org/10.1016/j.proeng.2017.10.555

Bang, J., Lee, D., Kim, Y., & Lee, H. (2017). Camera pose estimation using optical flow and ORB descriptor in SLAM-based mobile AR game. In *Proceedings of the 2017 International Conference on Platform Technology and Service* (*PlatCon*), Busan, South Korea. https://doi.org/10.1109/PlatCon.2017.7883693

Bouhamatou, Z., & Abdessemed, F. (2024). Visual simultaneous localisation and mapping methodologies. *Acta Mechanica et Automatica*, *18*(3), 451–462. https://doi.org/10.2478/ama-2024-0049

Chin, S., Kim, K., & Kim, Y. S. (2004). A process-based quality management information system. *Automation in Construction*, *13*(2), 241–259. https://doi.org/10.1016/j.autcon.2003.08.010

Chen, L., & Luo, H. (2014). A BIM-based construction quality management model and its applications. *Automation in Construction*, *46*, 64–73. https://doi.org/10.1016/j.autcon.2014.05.009

Chi, N. W., Chen, Y. W., Hsieh, S. H., Han, J. Y., & Huang, L. M. (2019). A BIM-based AR application for construction quality inspection. In *International Conference on Civil and Building Engineering Informatics* (*ICCBEI 2019*) (pp. 191–196), Sendai, Japan.

Calderon-Hernandez, C., & Brioso, X. (2018). Lean, BIM and augmented reality applied in the design and construction phase: A literature review. *International Journal of Innovation*, *Management and Technology*, *9*(1), 60–63. https://doi.org/10.18178/ijimt.2018.9.1.788

Cadena, C., Carlone, L., Carrillo, H., Latif, Y., Scaramuzza, D., Neira, J., Reid, I. & Leonard, J. J. (2016). Past, present, and future of simultaneous localization and mapping: Toward the robust-perception age. *IEEE Transactions on Robotics*, *32*(6), 1309–1332. https://doi.org/10.1109/TRO.2016.2624754

Chuang, T. Y., & Sung, C. C. (2020). Learning and SLAM based decision support platform for sewer inspection. *Remote Sensing*, *12*(6), Article 968. https://doi.org/10.3390/rs12060968

Chowdhury, T., Adafin, J., & Wilkinson, S. (2019). Review of digital technologies to improve productivity of New Zealand construction industry. *ITcon*, *24*, 569–587. https://doi.org/10.36680/j.itcon.2019.032

Dror, E., Zhao, J., Sacks, R., & Seppänen, O. (2019). Indoor tracking of construction workers using BLE: Mobile beacons and fixed gateways vs. fixed beacons and mobile gateways. In *Proceedings of the 27th Annual Conference of the International Group for Lean Construction* (*IGLC*) (pp. 831–842), Dublin, Ireland. https://doi.org/10.24928/2019/0154

Gashi, E. (2018). Management of defective works in infrastructure projects. *International Review of Applied Sciences and Engineering*, *9*(1), 73–80. https://doi.org/10.1556/1848.2018.9.1.10

Herrera, A. L. V., Tecson, P. D. I., Eduardo, J. T., Rosas, M. F., & Barrameda, R. B. (2019). Utilizing simultaneous localization and mapping (SLAM) in augmented-reality shell game for iOS. *TEST Engineering and Management*, *81*, 4973–4979.

Hsieh, S. H., Huang, B. K., & Kuo, W. L. (2023). *U.S. Patent No*. *11*,*631*,*195*. Patent and Trademark Office, Washington, DC: U.S.

Herbers, P., & König, M. (2019). Indoor localization for augmented reality devices using BIM, point clouds, and template matching. *Applied Sciences*, *9*(20), Article 4260. https://doi.org/10.3390/app9204260

Ibrahim, A., Faris, N., Zayed, T., Qureshi, A. H., Abdelkhalek, S., & Abdelkader, E. M. (2024). Application of infrared thermography in concrete bridge deck inspection: Current practices, challenges and future needs. *Nondestructive Testing and Evaluation*. https://doi.org/10.1080/10589759.2024.2443810

Jiang, J. R., & Subakti, H. (2023). An indoor location-based augmented reality framework. *Sensors*, *23*(3), Article 1370. https://doi.org/10.3390/s23031370

Kwon, O. S., Park, C. S., & Lim, C. R. (2014). A defect management system for reinforced concrete work utilizing BIM, image-matching and augmented reality. *Automation in Construction*, *46*, 74–81. https://doi.org/10.1016/j.autcon.2014.05.005

Krul, S., Pantos, C., Frangulea, M., & Valente, J. (2021). Visual SLAM for indoor livestock and farming using a small drone with a monocular camera: A feasibility study. *Drones*, *5*(2), Article 41. https://doi.org/10.3390/drones5020041

Lai, X., Kan, Z., Sun, W., Song, X., Tian, B., & Yuan, T. (2024). Digital twin-based non-destructive testing for structural health monitoring of bridges. *Nondestructive Testing and Evaluation*, *39*(1), 57–74. https://doi.org/10.1080/10589759.2023.2239434

Li, K., Tian, G. Y., Chen, X., Tang, C., Luo, H., & Li, W. (2019). AR-aided smart sensing for in-line condition monitoring of IGBT wafer. *IEEE Transactions on Industrial Electronics*, *66*(10), 8197–8204. https://doi.org/10.1109/TIE.2018.2886775

Li, N., & Becerik-Gerber, B. (2011). Performance-based evaluation of RFID-based indoor location sensing solutions for the built environment. *Advanced Engineering Informatics*, *25*(3), 535–546. https://doi.org/10.1016/j.aei.2011.02.004

Lin, I. C., & Dzeng, R. J. (2019). Developing anti-counterfeiting and error-proof mechanisms and automatic storage with construction inspection photos system. *Journal of the Chinese Institute of Civil and Hydraulic Engineering*, *31*(2), 173–182.

Lin, Y. C., Chang, J. X., & Su, Y. C. (2016). Developing construction defect management system using BIM technology in quality inspection. *Journal of Civil Engineering and Management*, *22*(7), 903–914. https://doi.org/10.3846/13923730.2014.928362

Liu, Y. C., Chen, J. R., & Chen, H. M. (2020). System development of an augmented reality on-site BIM viewer based on the integration of SLAM and BLE indoor positioning. In *Proceedings of the 2020 International Symposium on Automation and Robotics in Construction* (pp. 293–300), Kitakyushu, Japan. https://doi.org/10.22260/ISARC2020/0042

Liu, R., Zhang, J., Chen, S., Yang, T., & Arth, C. (2021). Accurate real-time visual SLAM combining building models and GPS for mobile robot. *Journal of Real-Time Image Processing*, *18*, 419–429. https://doi.org/10.1007/s11554-020-00989-6

Lee, C. W., Chondro, P., Ruan, S. J., Christen, O., & Naroska, E. (2018). Improving mobility for the visually impaired: A wearable indoor positioning system based on visual markers. *IEEE Consumer Electronics Magazine*, *7*(3), 12–20. https://doi.org/10.1109/MCE.2018.2797741

Mohanty, L., Chae, S., & Yang, Y. (2020). Identifying productive working patterns at construction sites using BLE sensor networks. *Developments in the Built Environment*, *4*, Article 100025. https://doi.org/10.1016/j.dibe.2020.100025

Ma, Z., Cai, S., Mao, N., Yang, Q., Feng, J., & Wang, P. (2018). Construction quality management based on a collaborative system using BIM and indoor positioning. *Automation in Construction*, *92*, 35–45. https://doi.org/10.1016/j.autcon.2018.03.027

Mirshokraei, M., De Gaetani, C. I., & Migliaccio, F. (2019). A web-based BIM–AR quality management system for structural elements. *Applied Sciences*, *9*(19), Article 3984. https://doi.org/10.3390/app9193984

Nguyen, P. T., Vo, K. D., Phan, P. T., Huynh, V. D. B., Nguyen, T. A., Cao, T. M., & Nguyen, Q. L. H. T. T. (2018). Construction project quality management using building information modeling 360 field. *International Journal of Advanced Computer Science and Applications*, *9*(10), 228–233. https://doi.org/10.14569/IJACSA.2018.091028

Neges, M., Koch, C., König, M., & Abramovici, M. (2017). Combining visual natural markers and IMU for improved AR based indoor navigation. *Advanced Engineering Informatics*, *31*, 18–31. https://doi.org/10.1016/j.aei.2015.10.005

Oufqir, Z., El Abderrahmani, A., & Satori, K. (2020). ARKit and ARCore in serve to augmented reality. In *Proceedings of the 2020 International Conference on Intelligent Systems and Computer Vision* (*ISCV*), Fez, Morocco. https://doi.org/10.1109/ISCV49265.2020.9204243

Omer, M., & Tian, G. Y. (2018). Indoor distance estimation for passive UHF RFID tag based on RSSI and RCS. *Measurement*, *127*, 425–430. https://doi.org/10.1016/j.measurement.2018.05.116

OMG. (2011). *Business process model and notation* (*BPMN*) *Version 2.0*, *Object management group specification*. https://www.omg.org/spec/BPMN/2.0/

Pratheesh Kumar, M. R., Reji, S., Abeneth, S., & Pradeep, K. (2020). On-site proactive construction defect management using mixed reality integrated with 5D building information modeling. *International Journal of Virtual and Augmented Reality* (*IJVAR*), *4*(1), 19–34. https://doi.org/10.4018/IJVAR.2020010102

Park, J., Cho, Y. K., & Martinez, D. (2016). A BIM and UWB integrated mobile robot navigation system for indoor position tracking applications. *Journal of Construction Engineering and Project Management*, *6*(2), 30–39. https://doi.org/10.6106/JCEPM.2016.6.2.030

Ratajczak, J., Riedl, M., & Matt, D. T. (2019). BIM-based and AR application combined with location-based management system for the improvement of the construction performance. *Buildings*, *9*(5), Article 118. https://doi.org/10.3390/buildings9050118

Rao, A. S., Radanovic, M., Liu, Y., Hu, S., Fang, Y., Khoshelham, K., Palaniswami, M., & Ngo, T. (2022). Real-time monitoring of construction sites: Sensors, methods, and applications. *Automation in Construction*, *136*, Article 104099. https://doi.org/10.1016/j.autcon.2022.104099

Sydora, C., & Stroulia, E. (2018). Augmented reality on building information models. In *Proceedings of the 9th International Conference on Information*, *Intelligence*, *Systems and Applications* (*IISA*), Zakynthos, Greece. https://doi.org/10.1109/IISA.2018.8633637

Shewail, S., Badr, M., & Tolba, A. (2024). Real-time indoor tracking for augmented reality using computer vision techniques. *International Journal of Advanced Computer Science and Applications*, *15*(2), 112–120. https://doi.org/10.11591/ijai.v13.i2.pp1845-1857

Sidani, A., Dinis, F. M., Duarte, J., Sanhudo, L., Calvetti, D., Baptista, J. S., Martins, J. P. & Soeiro, A. (2021). Recent tools and techniques of BIM-based augmented reality: A systematic review. *Journal of Building Engineering*, *42*, Article 102500. https://doi.org/10.1016/j.jobe.2021.102500

Shi, Y., Du, J., & Ragan, E. (2020). Review visual attention and spatial memory in building inspection: Toward a cognition-driven information system. *Advanced Engineering Informatics*, *44*, Article 101061. https://doi.org/10.1016/j.aei.2020.101061

Song, W., Lee, H., Lee, S. H., Choi, M. H., & Hong, M. (2018). Implementation of Android application for indoor positioning system with Estimote BLE beacons. *Journal of Internet Technology*, *19*(3), 871–878.

Tan, Y., Xu, W., Chen, P., & Zhang, S. (2024). Building defect inspection and data management using computer vision, augmented reality, and BIM technology. *Automation in Construction*, *160*, Article 105318. https://doi.org/10.1016/j.autcon.2024.105318

Tsai, Y. H., & Hsieh, S. H. (2016). Process modeling of a BIM-enabled construction inspection approach with BPMN. In *Proceedings of the 2016 International Conference on Innovative Production and Construction* (pp. 80–83), Perth, Australia.

Tsai, Y. H., Hsieh, S. H., & Kang, S. C. (2014). A BIM-enabled approach for construction inspection. In *Proceedings of 2014 International Conference on Computing in Civil and Building Engineering* (pp. 721–728), Orlando, Florida, USA. https://doi.org/10.1061/9780784413616.090

Thrun, S. (2007). Simultaneous localization and mapping. In M. E., Jefferies, & W. K. Yeap (Eds.), *Robotics and cognitive approaches to spatial mapping*: *Vol 38*. *Springer tracts in advanced robotics* (pp. 13–41). Springer. https://doi.org/10.1007/978-3-540-75388-9_3

Tseng, P. Y., Lin, J. J., Chan, Y. C., & Chen, A. Y. (2022). Real-time indoor localization with visual SLAM for in-building emergency response. *Automation in Construction*, *140*, Article 104319. https://doi.org/10.1016/j.autcon.2022.104319

Umer, W., & Siddiqui, M. K. (2020). Use of ultra-wide band real-time location system on construction jobsites: feasibility study and deployment alternatives. *International Journal of Environmental Research and Public Health*, *17*(7), Article 2219. https://doi.org/10.3390/ijerph17072219

Vasilyev, R. S., Losev, K. Y., Cheprasov, A. G., & Bektash, D. T. (2019). BIM and QR-codes interaction on a construction site. *Journal of Physics*: *Conference Series*, *1425*(1), Article 012089. https://doi.org/10.1088/1742-6596/1425/1/012089

Wei, Z., Chen, J., Tang, H., & Zhang, H. (2023). RSSI-based location fingerprint method for RFID indoor positioning: A review. *Nondestructive Testing and Evaluation*, *39*(1), 3–31. https://doi.org/10.1080/10589759.2023.2253493

Wu, H., Zhong, B., Li, H., Guo, J., & Wang, Y. (2021). On-site construction quality inspection using blockchain and smart contracts. *Journal of Management in Engineering*, *37*(6), Article 04021065. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000967

Walker, M. E., Hedayati, H., & Szafir, D. (2019). Robot teleoperation with augmented reality virtual surrogates. In *Proceedings of the 14th ACM/IEEE International Conference on Human-Robot Interaction* (*HRI*) (pp. 201–210), Daegu, South Korea. https://doi.org/10.1109/HRI.2019.8673306

Zhao, X., & Cheah, C. C. (2023). BIM-based indoor mobile robot initialization for construction automation using object detection. *Automation in Construction*, *146*, Article 104647. https://doi.org/10.1016/j.autcon.2022.104647

Zhang, S., He, Y., Gu, Y., He, Y., Wang, H., Wang, H., Yang, R., Chady, T., & Zhou, B. (2025). UAV based defect detection and fault diagnosis for static and rotating wind turbine blade: A review. *Nondestructive Testing and Evaluation*, *40*(4), 1691–1729. https://doi.org/10.1080/10589759.2024.2395363

Zhuang, S. (2020). *Real-time indoor location tracking in construction site using BLE beacon trilateration* [Master's thesis]. School of Science, Aalto University, Finland.