Inspection Data Exchange and Visualization for Building Maintenance using AR-enabled BIM

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Abstract

After the COVID-19 outbreak, a new concept of building maintenance (BM) systems is needed because current approaches highly rely on physical contact between workers, engineers, and managers. It imposes health and safety risks as increasing concerns about infections and spreads. This adds burdens to take unavoidable close contact and health risks to building owners, occupants, workforce, and society at large. In this respect, a new BM system was developed that enables reliable virtual communication and reduces BM response times by filling gaps between users and building managers. The proposed system is based on a concept of a cyber-physical system (CPS) using augmented reality (AR) and building information modeling (BIM) to promote non-contact building management. In this system, AR plays an important role in inspecting and visualizing defects in the real world, and the detected defect information is stored and managed by cloud-based BIM in cyberspace. This paper focuses on data visualization and management in the CPS-based non-contact building management system. A cloud-based database and mobile application are developed for data management purposes. In addition, this paper presents BIM data exchange and visualization in AR applications. Target image-based localization and tracking in BIM are also tested. The test results showed that the model alignment and localization accuracy are reliable for building maintenance works. Using the new BM mechanism, we expect that the related workers, building owners, and occupants will experience a reliable building maintenance process based on CPS-based information exchange from both users and facility managers while maintaining social distance.

Keywords –
BIM; AR; CPS; Building Maintenance System

1 Introduction

Although the accelerated number of vaccinations reduces the risk of infection, People's lives are still very different from before the Pandemic. After the outbreak of the tragic virus, many people want to minimize physical contact with others, and this trend may continue even after the COVID ends. For this reason, many health care and medical fields have been developing non-contact health care systems using cyber-physical systems (CPS) [1–3]. For example, Shah et al. presented a non-contact medical CPS framework with wireless sensing systems to monitor patients' physical activities [2], and Al-hababi et al. proposed a non-contact sensing network for post-surgery monitoring with artificial intelligence (AI) [3]. However, the study on non-contact systems for building maintenance and construction management is still lacking. Especially after the pandemic era, the need for the non-contact system is emphasized more because people spend more time indoors and are reluctant to physically contact others for maintenance and repair tasks.

Typical building maintenance is processed by the following steps: 1) reporting maintenance issues to facility managers or operators, 2) hosting a repairperson or contractor, 2) communicating face-to-face about the issue at hand, and 4) repairing defects and checking. Traditionally, physical contact between the occupants and maintenance workers is inevitable. Recently, some apartments have introduced a web-based maintenance system, in which the residents need to report the defects on the management website, and building managers carry out the maintenance work based on the resident's reports. In this way, the maintenance technicians can repair the reported defects without face-to-face instruction. However, repair request information provided by building occupants may be incomplete and inaccurate. For the correct maintenance work without the guidance of occupants, the occupants should fill in highly detailed information such as the type, location, and size of building objects where the defects are found. It can be troublesome, time-consuming work for nonprofessionals. Moreover, in most cases, the repairpersons leave a hand-written report for their maintenance jobs, which also makes it difficult for occupants to understand what is done. To address the challenges in the current BM process, this research intends to devise a contact-free process for building maintenance and repair by enabling non-contact communication and information transition between occupants and building managers in a cloud-based building information model (BIM)

BIM is an intelligent digital representation of a building or other infrastructure entity such as a road [4], bridges [5], and tunnels [6]. BIMs represent the digital revolution's most important contribution to the architecture/engineering/construction (AEC) industry. BIM can account for all components of a building, including walls, floors, ceilings, columns, stairs, railings, doors, windows, wiring, plumbing, and HVAC systems [7–10]. It can store semantic information that describes each component's appearance, dimensions, weight, material, thermal performance, and other physical properties [11]. BIM supports decisions [12] and facilitates convergent collaboration [13] throughout a building's life cycle. During the operation and building maintenance phase, BIM can help owners monitor, maintain, renovate, and repair a building [14], assure its security [15], optimize its safety [16], and track its assets [14]. Therefore, by offering a single source of building data and streamlining data exchange, implementing cloud-based BIM for non-contact BM systems can benefit a broad population of architects, engineers, contractors, facility operators and managers, and building occupants.

With the advantages of BIM, we propose a novel CPS using augmented reality (AR) enabled-BIM. The main objective of this system is to achieve non-contact building maintenance in preparation for post-COVID-19 by providing a way of managing inspection data in cloud-based BIM and visualizing inspection data with AR application. In the proposed system, the building occupants can upload maintenance requests simply with a smartphone app instead of a traditional burdensome reporting process. This research is driven by the hypothesis that the physical contact between the BM stakeholders can be reduced by enabling seamless communications between cyber and physical components while preserving individuals' privacy. The proposed CPS system automatically computes the user's location with visual-inertial odometry and identifies the type of objects and defects with deep learning technology. By doing that, this system automatically obtains all necessary information for building defects maintenance, and the collected information is uploaded to cloud-based BIM. By modeling an interoperable schema, the defect information is mapped to BIM, and the updated BIM is sent to the repairperson or facility managers. Among the proposed CPS component, this paper mainly focused on building inspection data management using cloud-based BIM and visualization using a mobile AR application. The following sections describe the way of exchanging and visualizing the building inspection data in CPS.

2 Related Works

Collaborative methods for BIM-AR technology have been employed to design, construction, and maintenance processes. By combining fuzzy multiple-criteria decision-making (MCDM), researchers can identify maintenance priorities among essential building information detected from BIM-AR applications [17]. However, BIM only provides static and predefined building data and information [18, 19] and may not contain target objects detected from AR. To update new building components, several ways of creating a new library of reusable parametric objects have been studied [20]. Parametric modeling using a scripting language and procedural modeling techniques using shape grammars can be combined and used for generating as-built BIM models. While procedural modeling enables automatic object generation and scalable geometric representation etc., manual methods are still required to create detailed elements [20]. Specifically, since the maintenance data is divorced from the BIM dataset [21], as-designed building information models do not contain an up-to-date status of buildings. For example, Construction operations building information exchange (COBie), a subset of the Industry Foundation Classes (IFC) schema, has been developed to collect data that can be used during operation and maintenance (O&M) stages [22]. However, COBie is non-geometrical data, so building models need to contain a high level of information, including installed conditions [22]. Although the COBie exports building elements data with their interdependent relationships, there are still missing links, and manual updates are necessary to maintain the recent building status [23]. COBie data exchange can also induce errors in the data transfer process [24]. Therefore, this research addresses current challenges of data exchange and updates in BM and intends to advance fundamental understanding of the feedback-loop formed during BM stages across building users, facility managers, and digitized building data and information. Another key challenge of cloud-BIM data transmissions is the lack of standardization [25]. The lack of cloud BIM-specific standards impedes BIM interoperability between data generators and feedback providers.

As discussed above, three major challenges need to be overcome before applying cloud-BIM and AR technologies to building management: 1) disconnections of BIM and AR, 2) one-way data transfer only from BIM to AR or other systems, and 3) lack of cloud standards for BIM data exchange and AR visualization. In this study, therefore, we present a way of exchanging and managing inspection data between AR and BIM and visualizing the information in AR applications.

3 Methodology

3.1 Human-in-the-Loop CPS (HiLCPS)

This research applied CPS concepts for building maintenance. One of the fundamental challenges in enabling field applications of CPS is the difficulty of digitalization and virtualization of physical data acquired in the real world. In the proposed system, the inspection data acquired by building occupants are automatically entered into the BIM model in cyberspace, and this information is then communicated back to maintenance workers in the real world. However, the existing BIM format does not have a data schema to digitalize and manage the damage information acquired from the AR application. Another distinct but related issue is the high dimensionality and the complexity of the physical world, with noisy, poorly collected, and uninterpretable data, which can cause difficulties in data communication between the physical world and cyber systems. In the proposed CPS system, the inspection or maintenance information collected from the physical world via smartphone should be mapped to the exact location in the 3D cyberspace.

One way to tackle these challenges is to create an artificial tunnel that connects cyberspace and the physical world [26]. In this pathway, the sensing data in the physical world is digitalized according to a predefined data schema, and the digitalized information is mapped to BIMs through the cyber environment. The updated BIM securely exports specific data for maintenance works via the artificial tunnel, and the exported information is visualized in the maintenance workers' AR app. For this purpose, this research aims to develop a human-in-the-loop CPS (HiLCPS) for non-contact building or building maintenance after the COVID-19 era. Figure 1 shows the HiLCPS concept of the proposed non-contact building maintenance system. In this loop system, the inspection information is generated by occupants, and maintenance workers perform repair works based on the given inspection information. The maintenance statement written by workers is delivered through the loop system, and then the occupants confirm if the maintenance is done right or not.

3.2 Data exchange in cloud-BIM using fiducial markers

The major challenge of updating cloud-BIM data is a lack of an open-source framework [27] and a break of cloud models from the original building dataset [21]. To address the challenge, we created a two-way information model that can bridge between cloud-BIM and AR-detected datasets by developing an interoperable schema. This task intends to enable the interoperability between AR and Cloud BIM for mutual communications between

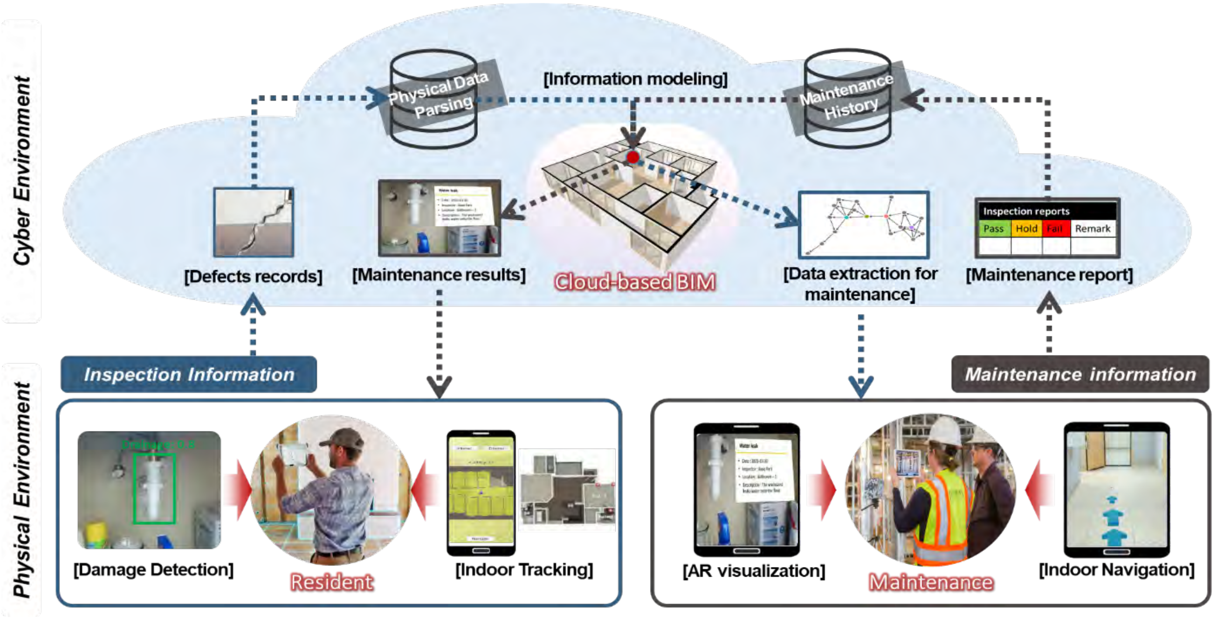


Figure 1. HiLCPS concept of the non-contact building maintenance system

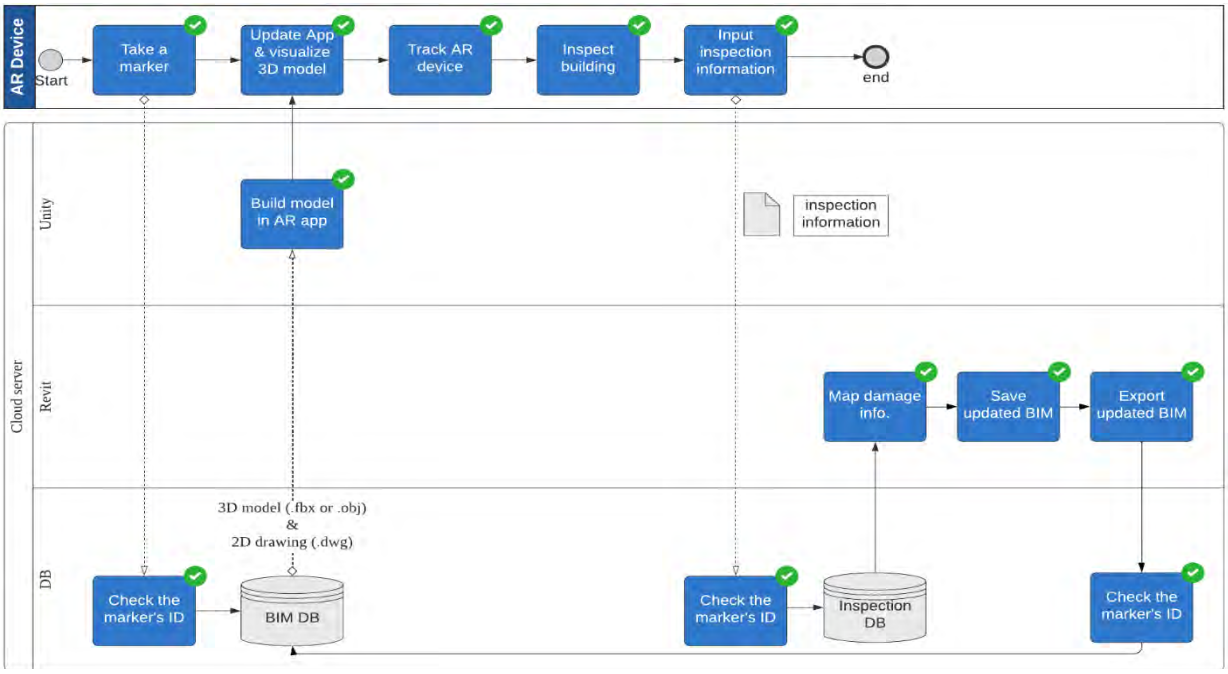


Figure 2. Data exchange model between the AR application and cloud-based BIM

multiple users and the proposed cyber-physical system and data exchange between two different systems of AR applications and Cloud BIM platform. This research team compared database schema, identified data loss, and built the integration by assembling building components in the original building models, cloud BIM, AR applications. Figure 2 shows the data exchange diagram. The integrated data schema can identify differences in the database in Cloud BIM platforms and AR applications, manage the effects of user inputs, and highlight and discover optimal information flow. The feasibility of the interoperable schema can be tested by modeling an integration task using DYNAMO, a combined environment of visual programming and textual programming. This research team also developed a DYNAMO script to access the AR database in BIM environments based on the integrated schema and verified the operational feasibility of the schema. The overall HiLCPS using the interoperable schema was tested its functions through a case study at an actual building. The outcome of integrating database schema can automate workflows of human inputs and building model updates and ultimately facilitate interactive communications of HiLCPS.

3.3 Indoor Localization and Model Alignment using Visual-Inertial Odometry (VIO)

For the fine localization and tracking of AR devices in GPS-denied environments, the AR camera's pose and location should be computed in real-time based on visual-inertial odometry (VIO). However, the VIO-based localization cannot express the absolute coordinate values with a single monocular camera on a mobile device. For this purpose, we developed a BIM-assisted depth estimation and localization method to compute the AR device's pose and to output absolute coordinates in a map. The BIM models can be imported by a fiducial marker, called AprilTag, attached to each maintenance unit (e.g., a room and an office). The AprilTags can also return a single pose at 6-degree of freedom (DOF) relative to the camera frame of reference. By doing so, the initial location and posture of the AR device can be located at a corresponding point in the BIM model. The BIMs imported to the AR scene assist in estimating initial location and global depth. The AR app then continuously estimates the camera's trajectory using VIO. The estimated 6-DOF is used for two functions of the application to be developed: 1) estimating the exact location of detected damages and 2) navigating maintenance workers to the location of the defects, as shown in Figure 3.

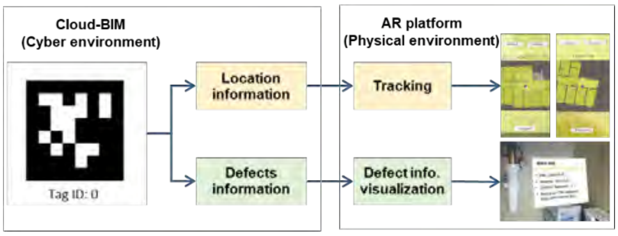


Figure 3. Localization and mapping in AR application using fiducial markers.

4 Case Study

4.1 Test Environment

To test the proposed HiLCPS-based building maintenance system, we conducted a case study in a one-story office building, as shown in Figure 4. The building was retrofitted in 2020, and there are a total of 14 rooms on both sides along the hallway. Through the case study, the performance of the data exchange between the AR application and cloud-based BIM using visual marker was tested. In addition, we also validated the accuracy of the localization and model alignment using VIO. A BIM was generated from the 2D drawings for building retrofit.

Figure 4. The outside and inside of the office building for test

4.2 Development Environment for the Building Maintenance System

For this test, we used an Apriltag for model alignment and multiple visual targets for localization. An Android smartphone with an operating system of 9.0 Pie was used during the test. The development environments for the database and AR application are:

- Spring Boot (4.11.0)
- MySQL (8.0.25.0)
- Unity (2020.3.13f1)

The file format for the 3D models imported to the AR application was Filmbox (.fbx), which is converted from Revit (.rvt) file through Dynamo. Two models, internal and external models, were generated from BIM, as shown in Figure 5. Tag ID #(1) assigned to the testing models.

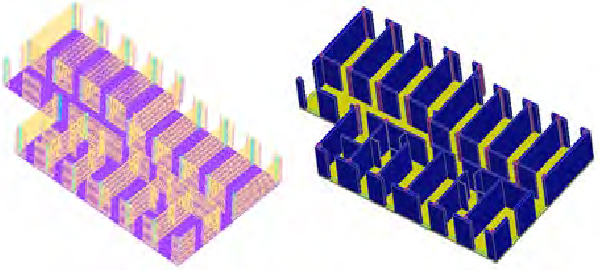


Figure 5. Internal 3D model (left) and external 3D model (right)

4.3 Test Result

4.3.1 Model Alignment

The accuracy of the model alignment was tested by measuring the discrepancies of real structure and visualized 3D model in the AR application. The 3D models are imported to the AR application by taking the Apriltag. Once the models are imported, the AR application visualizes the interior or exterior structure on the real-world scene. The AR application then tracks the position and pose of the mobile device in real-time with VIO. Therefore, the accuracy of model alignment and localization can be decreased as the distance from the fiducial marker increases. As described in Figure 6, The tests were performed on two walls 2 and 5 meters away from the fiducial marker. The measured alignment errors are described in Figure 7 and Table 1.

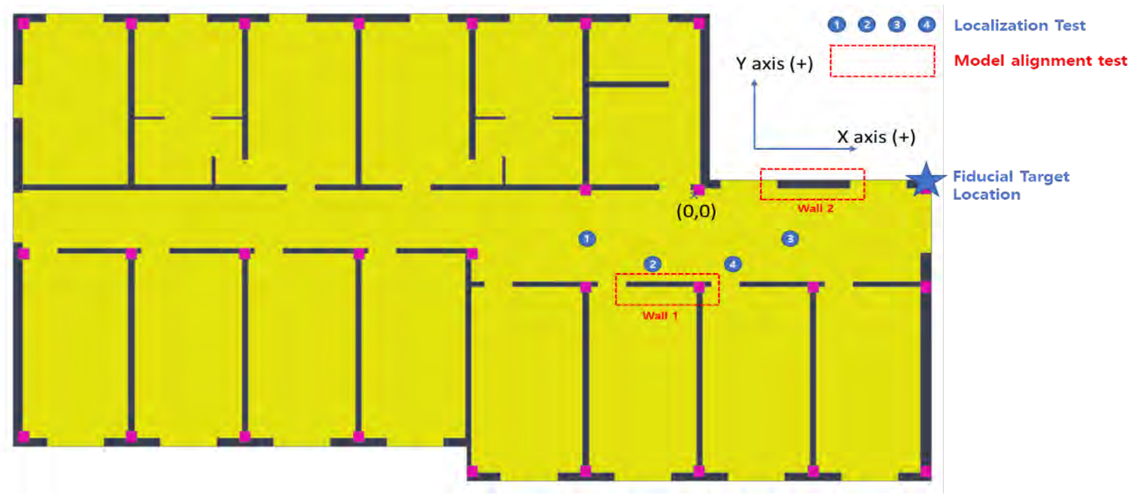


Figure 6. The positions for the localization test and model alignment test

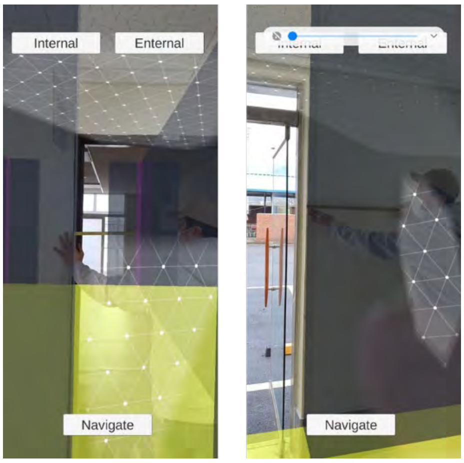


Figure 7. The model alignment test results: Wall 1 (left) and Wall 2 (right)

Table1. Measured model alignment errors

Target	Error (mm)	Error per meter from marker
Wall 1	12	2.4
Wall 2	10	3.3

4.3.2 Localization and Tracking

The accuracy of the localization using VIO was evaluated by measuring the position errors at four positions, as described in Figure 6. The XY coordinates indicated in the application are the coordinate system of BIM, and metric units are used. The ground truth positions were measured by a tape measure and a laser ranger. The results are demonstrated in Figure 8 and Table 2.

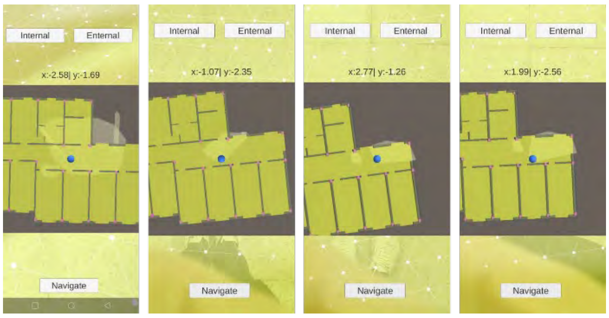


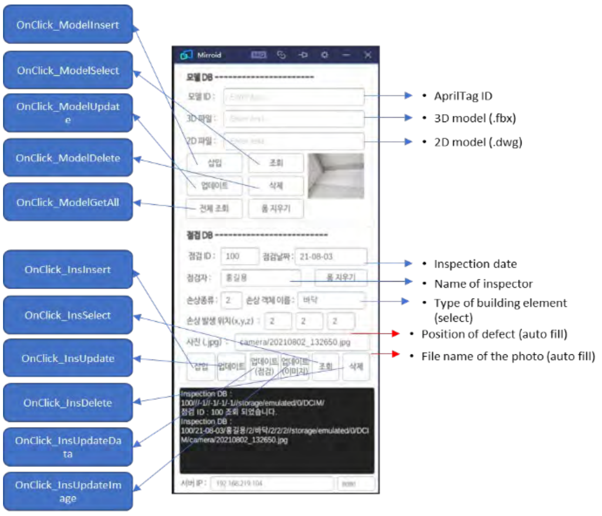
Figure 8. The localization test results at the test position 1, 2, 3, and 4

Table 2. Positioning errors

Target	Δx (m)	Δy (m)	Δxy (m)
Position 1	0.11	0.09	0.14
Position 2	0.10	0.12	0.16
Position 3	0.08	0.05	0.09
Position 4	0.10	0.15	0.18

4.3.3 Data Exchange

The mutual communications and data exchange between the AR application and the BIM database was carried out with a client application, as shown in Figure 9. The client app receives inspection and maintenance information from the mobile AR apps, formats it, and sends it to a web-based database. At this time, a predefined fiducial marker was used for model synchronization. Most of the inspection information, including the location of the observed damage, inspection date, and photos, is automatically entered into the client app. Figure 10 depicts the updated 3D assets in Unity with the inspection information collected from the AR application.



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Inspection DB :
100///-1//-1/-1/-1//storage/emulated/0/DCIM/
점검 ID : 100 조회 되었습니다.
Inspection DB :
100/21-08-03/홍길동/2/바닥/2/2/2//storage/emulated/0/DCIM/camera/20210802_132650.jpg
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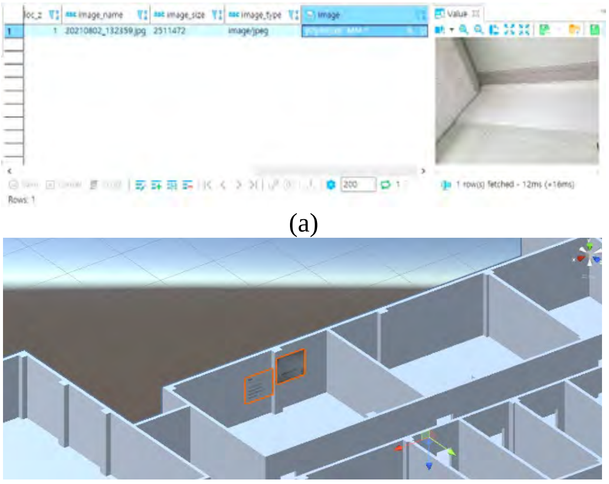
Figure 9. A client application for Inspection data management



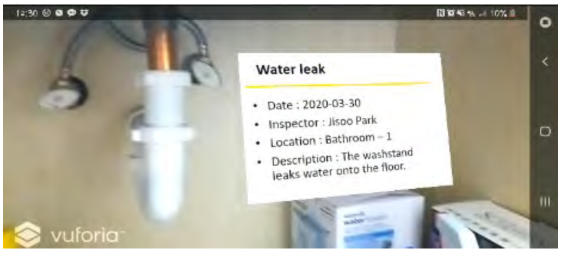
(a)

(b)

Figure 10. The inspection data management in web database (a) and 3D mapping on BIM

4.3.4 Data Visualization

The inspection information was managed by a web database, and the information could be mapped on BIM in real-time. The inspection information is then formatted in the Dynamo script as a text asset in the Unity application so that it can be visualized in the AR application. Figure 11 is a screen capture of the AR application visualizing the inspection information. For this test, we intentionally entered damage information into the inspection database. As shown in the figure below, the AR application visualized the damage information as a plain text box on the screen when the mobile phone camera was aimed at the location of the damage.



Water leak

- Date : 2020-03-30
- Inspector : Jisoo Park
- Location : Bathroom – 1
- Description : The washstand leaks water onto the floor.

Figure 11. Screen capture of the AR application showing the inspection information

5 Discussion

This research presented a building inspection data management and visualization method using AR-enabled BIM. To validate the presented methods, we conducted a case study at an actual office building. The test results showed that the AR application could visualize the 3D models in real-world view within 1.2 cm when the distance from the fiducial marker was 5 m. In addition, the positioning error was less than 2 cm, which is reliable for inspection data localization and user tracking. Finally, we also tested if the data exchange between BIM and AR applications works well through the data visualization test. We confirmed that the AR application was able to visualize the inspection information with a virtual text box at the correct location.

Although our test results were positive and reasonable, we also found some technical problems on model alignment and localization. The AR application was not able to track the rapid movement and motion change of the AR camera precisely. Hence, the user's sudden movement and motion change caused significant errors in localization and model alignment. To address this problem, we recommend using multiple fiducial markers. Since our AR application was designed to update the 6-DOF whenever the predefined AprilTag is displayed on the screen, the localization and model alignment error would be easily adjustable by employing multiple fiducial markers.

6 Conclusion

This research has three key scientific goals: (1) broadening understanding of Human-in-the-Loop Cyber-Physical Systems (HiLCPSs), (2) advancing fundamental knowledge on Cloud-BIM data interoperability, and (3) developing an integrative network of AR-enabled BIM. Through the practical intervention of two user groups, residents and facility managers, the cyber-physical system improves its reliability and usability. Also, to fill the gaps between as-built building information model (BIM) data and operation and maintenance information updates, a semantic data model employed in cloud BIM was developed. This system can be utilized to support housing management decisions by providing integrated and timely data.

We expect the research findings will innovate current building maintenance practices through reliable virtual operation, maintenance, and repair of buildings. By facilitating near real-time communications, the proposed method can detect various building operation issues promptly and reliably, including miscellaneous repair, major structural risks, or occupants' health and safety. In addition, we expect the non-contact building maintenance system can improve the security from infection of occupants in the COVID-19 era by eliminating physical contact between the occupants and maintenance workers.

Acknowledgments

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