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BIM-AR Driven Collaborative Management of Complex MEP Equipment Installation

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Abstract

With the increasing complexity of construction projects, the efficient installation and management of Mechanical, Electrical, and Plumbing (MEP) equipment has become particularly important. Currently, the management of complex MEP equipment faces challenges of multi-disciplinary collaboration, errors, and collisions during installation, as well as inefficient progress management and problem feedback. Therefore, this paper proposes a BIM and Augmented Reality (AR) driven collaborative management method for the installation of complex MEP equipment, including intelligent scene localization, accurate matching of model information, and collaboration of multi-terminal devices to reduce errors and improve efficiency. In this method, the physical built structural scene is firstly collected and accurately aligned with the MEP BIM model, and then the MEP component data is processed and matched using Dynamo and Unity. The human-machine interaction functions of installation guidance and review, information display and filtering, progress simulation, and data management are then realized for the complex MEP equipment. Additionally, the collaborative application and data management of multi-terminal devices utilizing AR headsets and handheld devices significantly improves the efficiency of communication. Through the experiment in a public building project under construction in Shenzhen, the feasibility and application effect of the method are verified, which provides strong support for the intelligent construction and collaborative management of complex MEP equipment, and has a wide range of application prospects.

Keywords: Augmented Reality, BIM, Collaborative Management, Human-machine interaction, MEP

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1 Introduction

The installation and management of mechanical, electrical, and plumbing (MEP) equipment face challenges as the scale and complexity of construction projects increase (Xie et al., 2022). Complex MEP equipment in this study refers to complex, narrow and curved MEP piping systems in large public buildings involving highly interwoven and space-constrained layouts, and traditional construction management methods have limitations in information transfer, progress control, and coordination (Li et al., 2022), which often lead to equipment installation conflicts, accuracy deviations, rework and schedule delays (Y. Wang et al., 2022; Zhao et al., 2021), thus affecting project quality and efficiency. Therefore, how to effectively manage complex MEP equipment and improve the level of construction intelligence is significant.

Building Information Modeling (BIM) technology provides a digital three-dimensional management platform for construction projects, which can realize information sharing in the design, construction, and operation phases (Vignali et al., 2021) . However, the application of traditional BIM models mostly stays at the design level, and the real-time interaction with the construction site is insufficient, especially in the installation guidance and schedule control of complex MEP equipment. Augmented Reality (AR) technology provides a new solution for the application of BIM in construction by virtue of the fusion of reality and reality (Chu et al., 2018) . Through AR devices, construction personnel can view the equipment installation location and parameter information in the BIM model in real time, which can dynamically guide the construction and reduce errors and communication costs. (Al-Sabbag et al., 2022; Catbas et al., 2022)

However, the existing combined BIM-AR applications mostly focus on the display of simple equipment, and lack systematic solutions for complex MEP equipment. In practical applications, there is still a lack of exploration on how to realize the accurate alignment of BIM model and field environment, the sharing of model geometry and semantic information, and the collaborative management of multi-terminal equipment.

To this end, this paper proposes a BIM-AR-driven collaborative management method of complex MEP equipment installation. First, a panoramic camera is used to capture the building scene to achieve high-precision alignment between the BIM model and the project scene. Subsequently, Dynamo and Unity are used to process and match the semantic information of components to ensure the sharing of BIM data among multiple devices. In the end, the head-mounted AR device and handheld device are used to realize installation guidance and review of hidden components, information display and screening, progress simulation, and data management among multiple devices, which improves the efficiency of construction management and collaboration level.

This paper is organized as follows: Section 2 reviews the research on the application of BIM in MEP and the application of AR in architecture; Section 3 introduces the methodology proposed in this paper and the implementation details; Section 4 shows the experiments and results in a public building project in Shenzhen; Section 5 summarizes the main conclusions and looks forward to the future direction.

2 Related Work

2.1 The Application of BIM in MEP

In recent years, with the rapid development of BIM technology, its application in MEP equipment has received wide attention. Pärn et al. (2018) investigated the application of BIM technology in multidisciplinary collaboration, but also pointed out that design conflicts still cannot be completely avoided in complex MEP equipment. J. Wang et al. (2016) developed a BIM framework that combines design, construction, and prefabrication, and it significantly improves the efficiency during the construction phase. In the O&M phase, Kalasapudi et al. (2014) demonstrated how laser scanning point clouds can be combined with BIM models for spatial analysis and facility management of MEP equipment, which provides effective support for long-term maintenance and operation, and Cheng et al. (2020) improved the efficiency of facility management of MEP equipment through the combination of BIM models and Internet of Things (IoT) technology.

Although BIM technology has shown many advantages in MEP facilities, there are still problems of design conflicts in multidisciplinary collaboration, lagging real-time feedback in the construction phase, and insufficient interaction between dynamic updates and actual scenarios in operation and maintenance.

2.2 The Application of AR in Construction

The application of AR in the construction field has gradually gained widespread attention, especially in construction management, quality control and safety monitoring, etc. (Nguyen et al., 2021; Sadhu et al., 2023). Morikawa & Ando (2019) developed an augmented reality-based pipeline management system, which recognizes and operates AR tags through a tablet computer. Park et al. (2013) proposed an AR-based defect detection system by combining BIM, AR and building defect management. Mirshokraei et al. (2019) developed a 4D BIM model using BIM and AR technology to enhance the quality management process in construction using AR. In the field of safety control, El Ammari & Hammad (2019) proposed a collaborative BIM-based augmented reality framework for supporting on-site safety inspections and remote collaboration. Diao & Shih (2019) developed an AR-based building maintenance system that provides safety training and real-time construction path guidance to ensure safe operation of workers.

Despite the progress of AR in the construction field, there is a lack of research on the accurate integration of AR with BIM geometric and semantic information, real-time dynamic interaction in complex environments, and collaborative management of multi-terminal devices. Meanwhile, the application of BIM-AR is limited by the computational capability and positioning accuracy, and the development and implementation costs are high, which makes it difficult to popularize it especially in large-scale projects.

Therefore, this study proposes a BIM-AR driven collaborative management method for complex MEP equipment installation. The method optimizes the management of MEP equipment by real-time data interaction and collaborative application of multi-terminal equipment through the accurate integration of AR and BIM model, and is applied in a large public building project, which fills the gaps in the existing research and has important practical application value.

3 Methodology

The framework diagram of the proposed method in this study is shown in Figure 1. It mainly includes the following four parts: (a) acquisition of building scene; (b) matching geometry and semantic information of model; (c) human-machine interaction application of complex MEP equipment; and (d) collaborative management of multi-terminal devices. In this section, the methodology of each part is described.

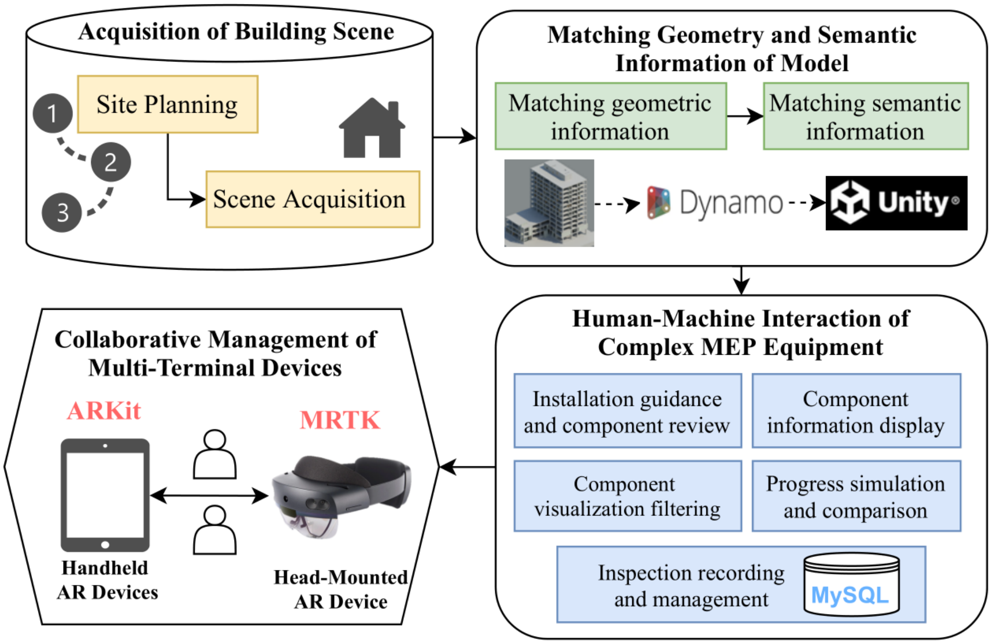


Figure 1. Framework diagram of the proposed method

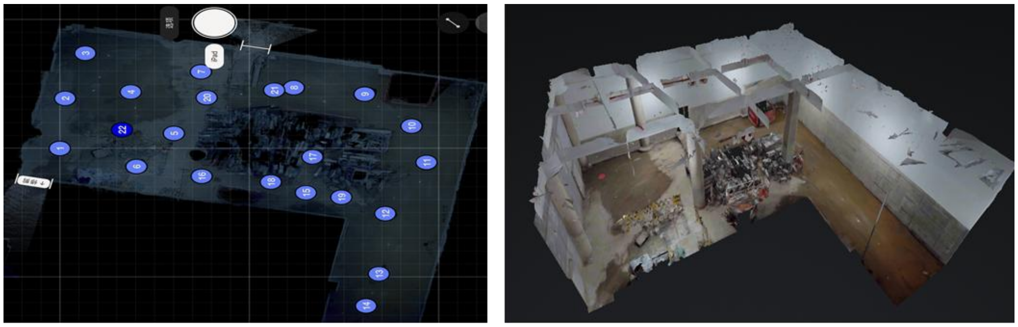
3.1 Acquisition of Building Scene

The acquisition of the building scene is a prerequisite to realize the AR effect. In this study, a Matterport Pro 2 panoramic camera is used to acquire the 3D scene inside the building and generate high-resolution 3D point cloud data and texture maps.

In order to ensure comprehensive coverage and high-precision acquisition of scene data, site planning for scenes is crucial. The spacing between sites is adjusted according to the spatial complexity and is usually set between 1.5 and 2.5 meters. At the same time, key locations such as windows and holes in the building are marked immediately after each acquisition operation to improve the matching effect.

After planning the sites, the Matterport Pro 2 panoramic camera performs a 360-degree omni-directional scanning at each acquisition site, combining with the depth sensor to capture spatial information of the scene and generating accurate point cloud data to represent the geometry of the building. At the same time, the high-resolution images captured by the camera are used to generate texture maps. The acquired sites are schematically shown in Fig. 2(a).

After the acquisition is completed, the system combines the texture mapping of each site with the point cloud data through a specialized processing algorithm to generate a 3D scene model with rich details and high-quality visual effects, which provides a reliable reference for the geometrical alignment of the BIM model, as shown in Figure 2(b).



(a) Site planning

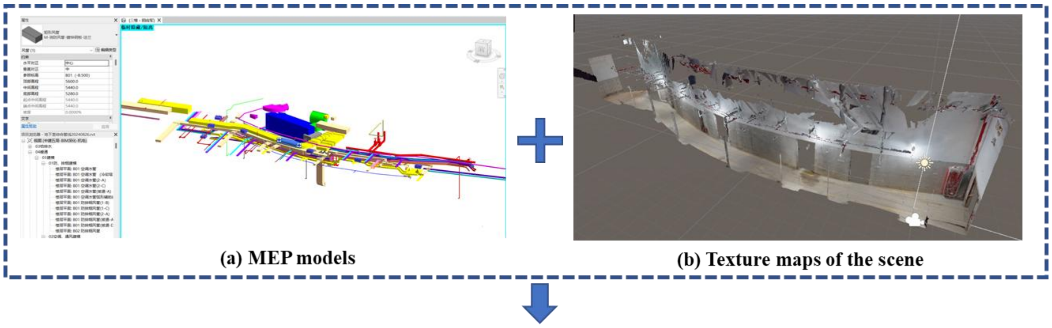
(b) 3D scene model

Figure 2. Acquisition of building scenes

3.2 Matching Geometric and Semantic Information of Model

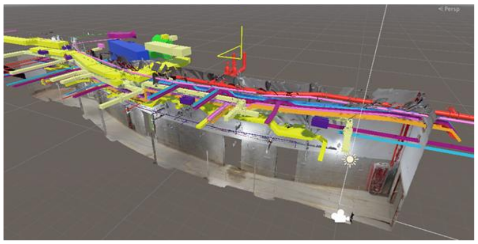
(1) Matching Geometric Information of Model

In the process of geometric alignment of MEP models, this study adopts a markerless-based matching method to accurately align the existing MEP models linking architectural and structural models with the captured texture maps of the scene, and the results are shown in Figure 3.



(a) MEP models

(b) Texture maps of the scene



(c) Matching effect

Figure 3. Markerless-based matching method for geometric information

The key to the matching process is to select a number of obvious architectural reference points, such as columns, wall corners and other geometric feature points. Based on the coordinate relationships of these reference points, the matching algorithm calculates the transformation matrix and automatically adjusts the position, angle and scale of the MEP model to ensure that it is completely consistent with the geometry and spatial location of the actual built environment. The advantage of this automatic markerless-based matching method is its flexibility and accuracy, which is more efficient than the traditional manual adjustment and can adapt to the complex geometry of different building environments.

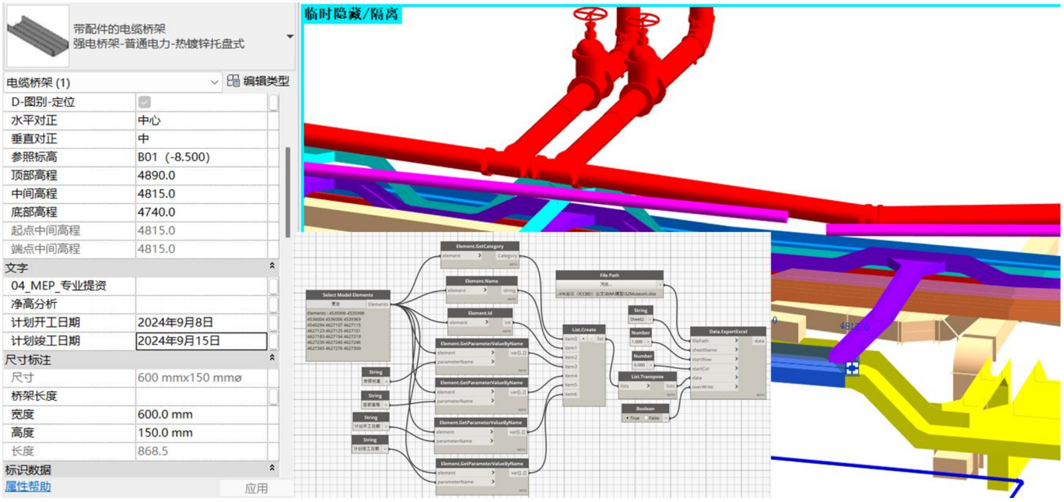
In addition, this study is based on Vuforia's Area Target localization technology, which generates feature maps by capturing the salient geometry of the target area. When the AR device scans the physical environment in real time, the system automatically compares the environmental features captured by the camera with the pre-generated feature maps, thus realizing the precise alignment between the virtual model and the actual scene.

In this way, the MEP model can be accurately superimposed in the augmented reality environment, which provides a reliable location basis for construction guidance, on-site inspections, and so on.

(2) Matching Semantic Information of Model

The matching of semantic information enables the virtual model not only to have physical geometry but also to display detailed component attributes in an augmented reality environment. These attributes include key information such as the ID, category, construction period, and floor of the MEP component.

The semantic information of the components is exported from the BIM model by writing a program in Dynamo, as shown in Figure 4. The exported data forms a semantic information table corresponding to the geometric model. This information table provides rich data support for subsequent matching and interaction operations.



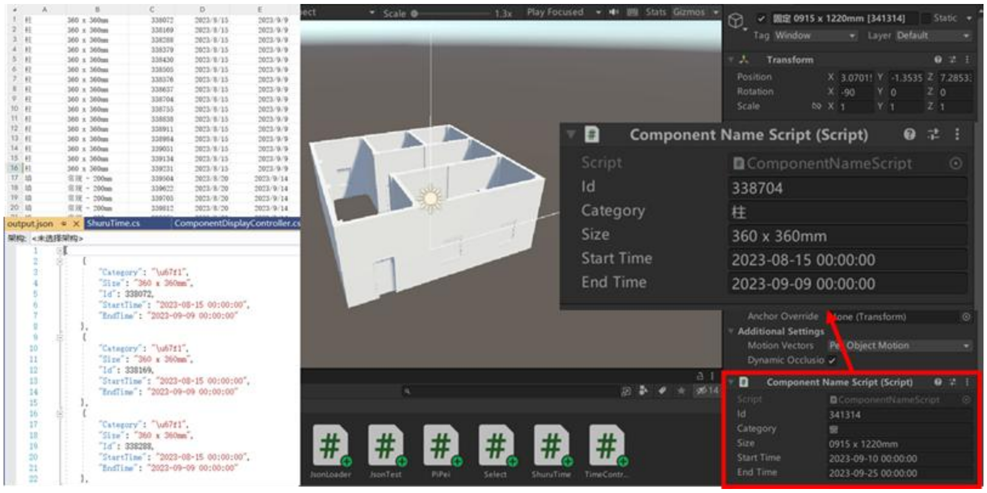
带配件的电缆桥架
强电桥架-普通电力-热镀锌托盘式

电缆桥架 (1)

D-图别-定位	☑
水平对正	中心
垂直对正	中
参照标高	B01 (-8.500)
顶部高程	4890.0
中间高程	4815.0
底部高程	4740.0
起点中间高程	4815.0
端点中间高程	4815.0
文字	
04_MEP_专业提资	
净高分析	
计划开工日期	2024年9月8日
计划竣工日期	2024年9月15日
尺寸标注	
尺寸	600 mmx150 mmø
桥架长度	
宽度	600.0 mm
高度	150.0 mm
长度	868.5
标识数据	

Figure 4. Component information export by Dynamo

Next, the exported semantic information needs to be matched with the model artifacts in the Unity environment. After the BIM model is imported into Unity, each component's name contains a unique ID that corresponds to the ID exported by Dynamo. With this unique identifier, the semantic information can be accurately associated with the geometry model in Unity, realizing the fusion of geometric and semantic data. An example of associating semantic information in Unity is shown in Figure 5.



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output.json  ShuruTime.cs  ComponentDisplayController.cs
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        "StartTime": "2023-08-15 00:00:00",
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    },
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    },
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Component Name Script (Script)
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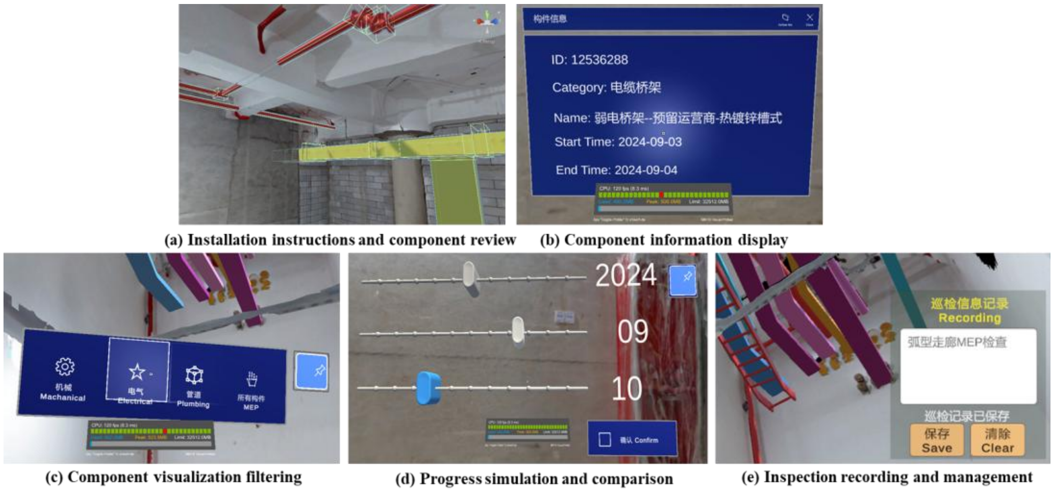
Id: 338704
Category: 柱
Size: 360 x 360mm
Start Time: 2023-08-15 00:00:00
End Time: 2023-09-09 00:00:00

Component Name Script (Script)
Script: ComponentNameScript
Id: 341314
Size: 0915 x 1220mm
Start Time: 2023-09-10 00:00:00
End Time: 2023-09-25 00:00:00

Figure 5. Matching semantic information in Unity

3.3 Human-machine Interaction Application of Complex MEP Equipment

Based on the acquisition and matching of MEP component data, this paper proposes a set of AR-based human-machine interaction application solutions. By combining the components in the MEP model with the actual scene, this solution realizes efficient component installation guidance, information display, progress management and inspection records in the AR environment, and its effect is shown in Figure 6.



构件信息
ID: 12536288
Category: 电缆桥架
Name: 弱电桥架--预留运营商-热镀锌槽式
Start Time: 2024-09-03
End Time: 2024-09-04

(a) Installation instructions and component review (b) Component information display

(c) Component visualization filtering (d) Progress simulation and comparison (e) Inspection recording and management

Figure 6. Human-machine interaction application of complex MEP equipment

(1) Installation Guidance and Component Review

During the installation of complex MEP equipment, the accurate AR positioning effect setting can visualize the installation position of each component and provide clear guidance to the construction personnel, such as the location of holes and the determination of the installation sequence. In addition, AR technology also supports the review of hidden components, the effect of which is shown in Figure 6(a). The feature helps constructors quickly understand the arrangement of complex equipment, reduces installation errors, and improves installation efficiency.

(2) Component Information Display

In the AR scene, the detailed attribute information of the components can be displayed in real time by interacting with the model, the effect of which is shown in Figure 6(b). Through the development of collision bodies, pointers and rays, construction personnel can select any MEP component by simple gesture operation and display its ID, category, duration and other attributes, so that construction personnel can quickly determine the specific installation requirements and status of the component.

(3) Component Visualization Filtering

In order to help constructors quickly locate and view specific types of components, the application performs visual filtering based on the category, floor, room and other attributes of the MEP components. Users can filter out specific categories of MEP components through simple menu operations, which can reduce visual interference and quickly locate the required components, the effect of which is shown in Figure 6(c).

(4) Progress Simulation and Comparison

The progress simulation function allows the user to set the construction date in the AR scene. As shown in Figure 6(d), when the user sets a certain date, the AR scene will display all the components that should be completed before that date. Users can visually check whether the components are completed on schedule, which helps managers adjust the construction plan in time and provides a powerful support for the construction progress management of MEP equipment.

(5) Inspection Recording and Management

On the construction site, the recording and management of inspection information is an important part of ensuring the quality of construction. The AR system in this study manages all the inspection records through MySQL database and supports the synchronized operation of multiple terminal devices. As shown in Figure 6(e), the construction personnel can record the inspection results after completing the component inspection in the AR scene, and the system will automatically upload this information to the MySQL database for subsequent query and management, ensuring that the problems in the construction process will be fed back and solved in a timely manner, which improves the efficiency of construction management.

3.4 Collaborative Management of Multi-Terminal Devices

This study introduces AR headset and hand-held devices into on-site construction management, realizing the collaborative management of multi-terminal devices. Through the database, the inspection information is unified and synchronized in real time among multiple devices, and the managers and construction personnel can use different devices to view and update the equipment information in real time, which improves the communication and collaboration efficiency at the project site.

(1) Deployment of AR Headset

HoloLens 2 provides an immersive 3D visualization experience. Combined with Microsoft's Mixed Reality Toolkit (MRTK), an application was developed that allows users to view component properties, check construction progress, and enter inspection information into the system for management through gesture presses, hand rays, or voice commands. Through multiple rounds of deployment testing, its UI design was optimized to enable stable operation in complex field environments and seamless collaboration with other devices.

(2) Deployment of AR Handheld Devices

Handheld devices such as iPad are widely used in project sites due to their portability and ease of operation. iPad provides real-time access to project data and recording of inspection results, and the developed UI interface focuses on touch-screen interaction and supports zooming in and out of the 3D model, rotating the viewing angle and component filtering. Users can filter MEP components according to floor, category and other conditions, and inspection data is automatically uploaded and synchronized to the database. Deployment tests of AR kit show that it performs stably in scenes with poor signal or complicated construction, especially suitable for frequently moving occasions.

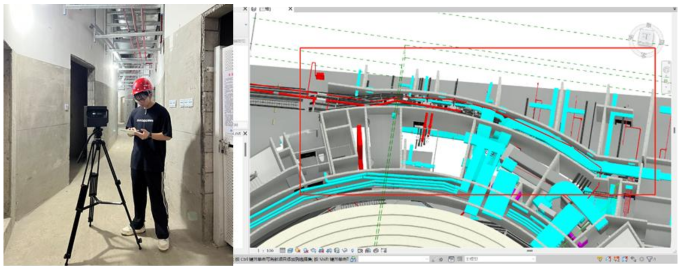
4 Experiments

In order to verify the feasibility and application effect of the proposed method in this study, experiments were conducted in the basement MEP equipment scenario of a public building project under construction in Shenzhen. The experiments mainly focus on the matching accuracy of geometric and semantic information of MEP models, the application effect of human-machine interaction of complex electromechanical equipment, and the collaborative application of multiple terminals to validate its practical value for MEP equipment installation and management.

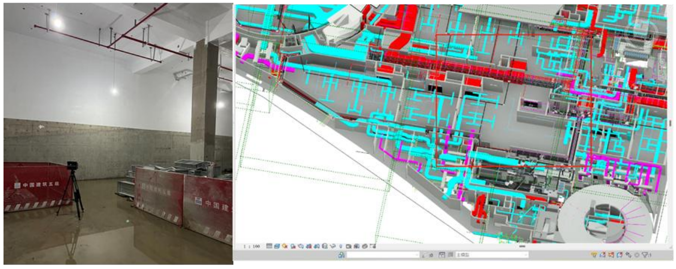
4.1 Experimental Setting

Two complex areas in the negative basement floor were selected for the experimental scenario: a curved corridor and a large room, as shown in Figure 7. The corridor area contains complex piping and ventilation equipment, while the room involves the installation and commissioning of multiple MEP equipment.

In order to ensure accurate data acquisition and precise model alignment, the experiments were conducted using a Matterport Pro 2 panoramic camera for on-site 3D scanning, Revit 2020 for processing the MEP model, Dynamo for developing a program for exporting the MEP component data, and Unity 2020 and 2021 for the development of UWP and IOS versions of the AR apps, respectively. HoloLens 2 and iPad Pro were used for AR human-machine interaction in the field.



(a) Scene 1 Museum curved corridor



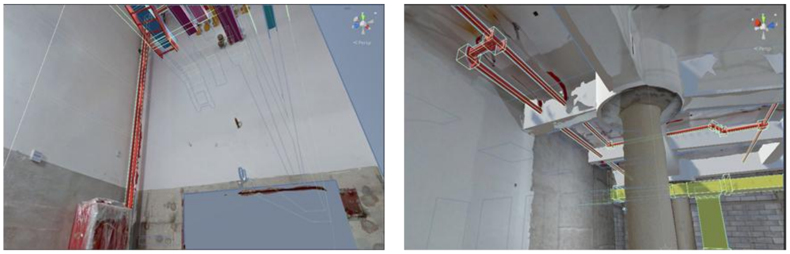
(b) Scene 2 Museum room

Figure 7. Experimental scenes and acquisition

4.2 Experimental Implementation and Results

(1) Matching of Model Information

The experiment captured 3D texture maps of two scenes by Matterport Pro 2 and accurately aligned the scenes with the BIM models in Unity. The columns and corners in the building were selected as reference points during the matching process to ensure the precise alignment of the MEP model with the actual environment. At the same time, the semantic data of the MEP components exported by Dynamo are bound in Unity to realize the integration of geometric and semantic information of the virtual model. As shown in Figure 8, the geometric positioning error of the model reaches centimeter level, and the semantic data is matched accurately, which can display the detailed attribute information of the components in the AR scene in real time.



(a) Scene 1: Matching by reference points **(b) Scene 2: Matching by reference points**

(c) Scene 1: Positioning accuracy **(d) Scene 2: Positioning accuracy**

Figure 8. Matching effect of model information

(2) Human-Machine Interaction Applications on AR Headset

On the HoloLens 2 device, the experimenter was able to visualize the 3D model of the MEP equipment through the AR environment. By interacting with the virtual model through gestures and voice commands, the constructor was able to obtain component information, check the installation location, and review the status of hidden components in real time, the effect of which is shown in Figure 9. The experimental results show that the HoloLens device can accurately display the installation position of the MEP equipment, the superposition of the AR model and the actual space is good, the program can run at a frame rate of up to 60 FPS, with an average frame rate of 46 FPS, and the operation is smooth, which significantly improves the visualization effect of the construction of complex MEP equipment.

构件信息

ID:

Category:

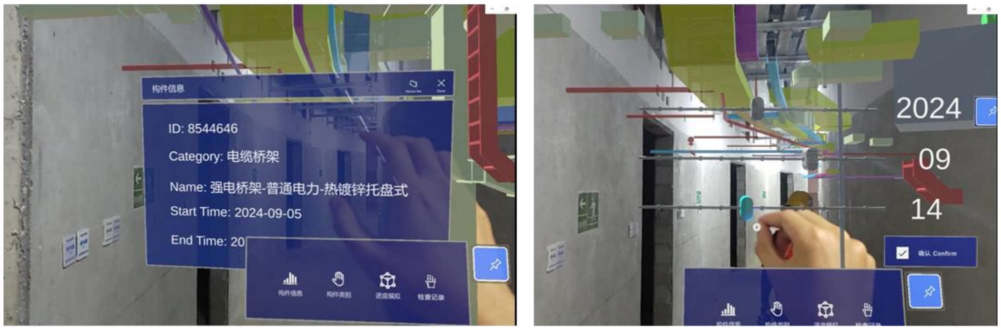
Name:

StartTime:

Endtime:

巡检信息记录:......

(a) UI on the HoloLens 2



构件信息

ID: 8544646

Category: 电缆桥架

Name: 强电桥架-普通电力-热镀锌托盘式

Start Time: 2024-09-05

End Time: 20

(b) Component information display **(c) Progress simulation and comparison**

Figure 9. Human-machine interaction applications on HoloLens 2

(3) Human Machine Interaction Applications on AR Handheld Devices

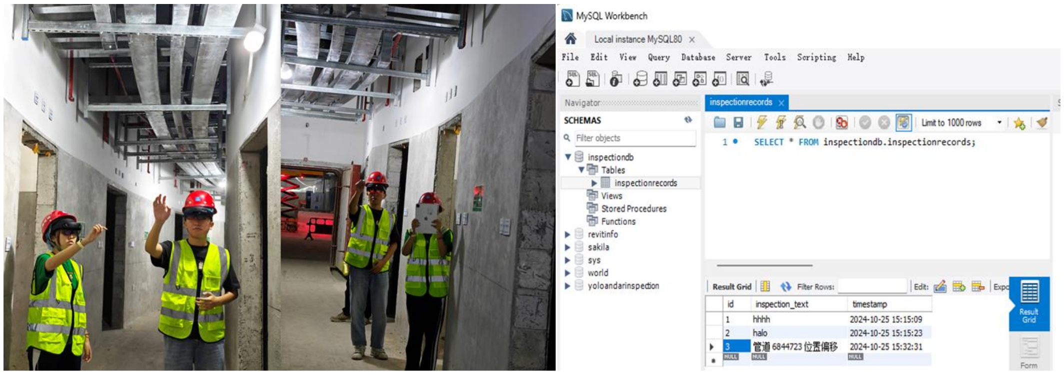
On the iPad Pro, the experimenter was able to view and query the information of MEP components through touch screen operation. As shown in Figure 10, the intuitive interactive interface allows users to quickly click on the components to view their attributes and use the filtering function to categorize and display the components according to conditions such as floor and category. The experimental results show that iPad Pro has fast response time for data loading and operation, stable enhanced localization effect, and high portability, which is suitable for quick inspection and information query in mobile scenes, and has more flexibility compared with HoloLens 2.

构件信息
Component Information
ID: 12975979
Category: 风管
Name: M-空调通风-镀锌钢板-法兰
Start Time: 2024-09-08
End Time: 2024-09-15

Figure 10. Human-machine interaction applications on iPad Pro

(4) Collaborative Management of Multi-Terminal Devices

In the multi-terminal collaborative application experiment, the collaborative application of devices such as HoloLens 2 and iPad Pro can better communicate about the situation of complex MEP equipment, and at the same time synchronize the inspection data through the MySQL database, and the experimental effect is shown in Figure 11. The experiment shows that the multi-terminal collaborative application significantly improves the information sharing and communication efficiency at the project site, and the construction personnel and management personnel are able to provide real-time feedback on the problems through different devices and ensure the unified management of inspection records.



```
SELECT * FROM inspectiondb.inspectionrecords;
```

id	inspection_text	timestamp
1	hhhh	2024-10-25 15:15:09
2	halo	2024-10-25 15:15:23
3	管道 6844723 位置偏移	2024-10-25 15:32:31
NULL	NULL	NULL

(a) Collaboration of multi-device terminals **(b) Management of inspection records**

Figure 11. Collaborative Management of Multi-Terminal Devices

4.3 Experimental Summary

The method proposed in this study is effectively verified through experiments in the MEP equipment scenario in the basement of a public building project under construction in Shenzhen. The experimental results show that the method can achieve centimeter-level accuracy in the localization of model geometric information, and at the same time, the semantic information of components can be accurately matched. The enhanced visualization effect of multi-terminal AR devices is obvious, in which the HoloLens 2 program can run at a frame rate of up to 60 FPS in the field, with an average frame rate of 46 FPS, and the collaborative application improves the efficiency of communication and feedback in the field. Overall, this method can smoothly realize the interaction of complex MEP equipment, significantly improve the efficiency of equipment installation and collaborative management, and has high practical application value.

5 Conclusions

This study proposes a BIM-AR-driven collaborative management method for complex MEP equipment, which significantly improves the efficiency of MEP equipment installation management through the acquisition of architectural scenes, the high-precision matching of model geometry and semantic information, and the collaborative application of multi-terminal devices. The introduction of AR technology enables construction personnel to interact with the virtual model in a real environment, realizing installation guidance, component information display, progress simulation and other human-machine interaction functions, which greatly improves the intuitiveness and accuracy of on-site operation. Through the experimental verification in a public building project under construction in Shenzhen, this method shows good feasibility and application prospects in real projects.

However, this study still has some shortcomings in practical application. First, although AR significantly improves the interactive experience, the stability of the equipment and the real-time data transmission still need to be further optimized in the complex construction environment. Second, the synchronization of BIM data across multiple devices needs to be further optimized to ensure seamless communication and real-time updates. Future work will focus on improving the scalability of the system in large-scale projects, optimizing the data transmission and multi-terminal collaboration mechanism, and exploring advanced features such as automated management and machine learning-based detection to further enhance the intelligence of MEP equipment management

Acknowledgments

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