BIM-Integrated AR for MEP field inspection: A Multi-modal Approach

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Abstract

On-site inspection of mechanical, electrical, and plumbing (MEP) installations is often inefficient because 2D drawings are unintuitive, making it difficult for engineers to interpret complex spatial relationships and retrieve relevant information quickly. To bring BIM information to the point of work, this study proposed a BIM-integrated augmented reality (AR) multi-modal prototype that supports in-situ visualisation of MEP components and rapid retrieval of key BIM attributes during inspection. The prototype was evaluated in a real construction setting with 91 engineers. The results indicate that the proposed approach streamlines information access and improves the accuracy, demonstrating the feasibility of BIM-integrated AR for routine MEP quality control. These results provide empirical evidence for deploying lightweight AR-enabled BIM workflows to improve on-site inspection efficiency.

Keywords –

Augmented reality; BIM; MEP; Onsite Inspection

1 Introduction

Mechanical, electrical, and plumbing (MEP) inspection is a frequent but time-consuming activity in a construction project [1]. Inefficient checking and late discovery of installation deviations often lead to rework and increased cost [2]. In practice, many inspection tasks still rely on 2D drawings, which are not sufficiently intuitive for interpreting complex MEP layouts [3].

Building Information Modelling (BIM) has improved MEP coordination during design by enabling 3D modelling and clash detection. from the design intent, meaning that conflicts may However, this clash detection does not guarantee error-free construction. Installation tolerances, on-site adjustments, and sequencing constraints can introduce deviations still emerge during construction even when the BIM model is well coordinated [4].

A solution proposed by previous research is to capture as-built conditions via 3D scanning and compare point clouds with the design BIM model [5, 6]. While effective for certain quality assurance tasks, scan-to-BIM workflows often involve complex procedures and limited real-time capability, which restrict their use for frequent daily inspection [7]. Overall, scan-to-BIM improves as-built verification, but it rarely provides immediate BIM information for onsite inspectors during ongoing installation. This limitation leaves BIM largely "office-bound," with limited utilisation at the point of work at construction sites.

Augmented Reality (AR), defined as technology that overlays computer-generated information onto a user's view of the real world [8], offers a promising pathway to bridge this gap. Through spatial registration, AR can align BIM 3D models with the physical environment and present attributes of each building component in situ, which allows engineers to interpret complex MEP layouts and access relevant BIM information directly where the work is installed [9]. The delivery of 3D context is difficult to achieve with conventional drawing-based approaches, which require manual interpretation and repeated cross-referencing between paper (or 2D views) and the site. Consequently, AR can enable BIM to be used directly on-site during construction, supporting daily MEP inspection and quality control.

Prior studies have explored BIM–AR integration for construction tasks. A study proposed a tablet-based system that overlays BIM models of building components onto the real site in real time. The system also allows engineers to access drawings on site at any time. With these functions, users can directly compare the BIM design with field conditions and incorporate on-site information that is not captured in the BIM model [3]. Another study has explored BIM–AR integration for rapid exterior inspection using drones. BIM models were overlaid directly onto the drone's camera view, and inspectors could query BIM attributes from the aligned model. This setup enables faster visual checks and can improve the efficiency of routine inspection workflows [10]. Zheng, et al. [11] proposed a prototype that visualised the onsite simulation of MEP installation progress. The progress timeline was extracted from Revit, and the system also included a reporting function that enabled onsite feedback to be sent back to Revit. Other studies have also proposed integrating AR with BIM to improve inspection efficiency and reduce engineers' workload [1, 12, 13].

Existing studies have demonstrated the concept and feasibility of BIM–AR integration. However, evidence from real construction-site MEP scenarios remains limited. In particular, there is a lack of field evaluations conducted with practising engineers on work sites, including direct comparisons with conventional drawing-based inspection. Existing studies tend to prioritise usability testing, while evidence from real-site trials with practising engineers, especially regarding the actual performance improvements enabled by BIM-integrated AR in MEP inspection, remains limited, constraining the development of actionable deployment guidelines.

To address this gap, this paper presents a BIM-integrated AR prototype for on-site MEP inspection and reports a field evaluation with 91 practising engineers in a construction setting. The prototype was developed based on existing prototypes proposed by previous researchers, but its interaction was redesigned to provide a clearer and more user-friendly working environment. The evaluation is organised around two realistic inspection tasks and measures both inspection time and accuracy, enabling a direct comparison between BIM-integrated AR workflows and conventional drawing-based practices. Importantly, we further compare two representative AR deployment options—tablet-based AR and a head-mounted display (HMD)—to examine how device form factors shape inspection performance and on-site usability constraints. On the academic side, the study provides field-based evidence of when and to what extent BIM-integrated AR can improve time efficiency and inspection accuracy under real construction conditions. Practically, the results translate into deployment-oriented guidance for routine MEP quality control, clarifying the performance–usability trade-offs between tablets and HMDs and outlining where each device fits best in everyday site workflows.

This study contributes by extending existing AR-based inspection prototypes toward real-world construction application. Based on prior research on AR for inspection, this paper refined the interaction design to better fit field inspection practice. The paper compared two representative AR platforms, handheld AR and head-mounted AR, to further examine how device form affects inspection performance. Most importantly, the study was conducted in a real construction project with practising engineers, which moves the discussion from controlled prototype demonstration toward practical deployment in actual site inspection.

2 System Development

Two on-site MEP engineers were interviewed to gather requirements and inform the prototype design. After the initial design the same engineers tested the system in the target inspection area. Their feedback was then used to refine the interface and key functions through iterative revisions. This section describes the system details and the engineer-based testing.

2.1 System Architecture

The proposed system adopts an architecture that integrates 3D model preparation and BIM information extraction, on-device fusion of geometry and BIM information, and on-site issue reporting and feedback (Fig. 1; blue, yellow, and red arrows, respectively).

MEP elements were extracted from the Revit BIM model in two parts: a 3D geometry model and component information. The geometry model was simplified by removing unnecessary objects and reducing polygon counts, and then imported into the client for real-time rendering. In parallel, component information was extracted for each MEP element, including basic geometry parameters and relevant attributes. All information was consolidated and exported as a JSON file.

Both the simplified 3D geometry model and the JSON file were loaded into the client, where each 3D element was linked to its component ID. This linkage allows the client to retrieve the full component information by ID. During on-site inspection, selecting a pipe or duct model immediately displays its associated BIM information.

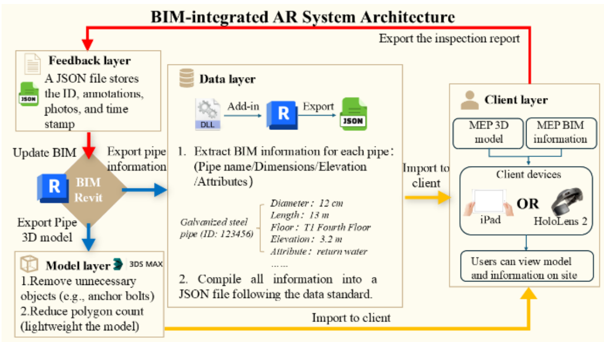

Figure 1 System Architecture of the proposed system

The client also provides an issue reporting function.

Inspection feedback is saved as a structured report containing the IDs of elements with issues, report time, and notes. The report can be sent back to the BIM environment, where the problematic elements are quickly located by ID for correction and model update.

2.2 Hardware and Software

The client was deployed on two hardware platforms: a 10th-generation iPad and a Microsoft HoloLens 2. Both platforms provide the same functions but use different interaction methods. The iPad supports direct touch input on the screen, whereas the HoloLens 2 uses hand-gesture interaction. Using both devices also enables comparison of their on-site performance.

On the iPad, the application was developed with Vuforia (V11). Device pose tracking relies on Vuforia's vision-based tracking combined with the built-in IMU. The alignment between the MEP model and the real world is achieved using QR-code markers placed in the inspection area; once a QR code is detected, the virtual model is registered to the physical environment.

On the HoloLens 2, the application was developed with Mixed Reality Toolkit 3 (MRTK3). Tracking similarly integrates vision and IMU data, and Microsoft's World Locking Tools were used to maintain a stable spatial relationship between the 3D model and the real world. Alignment was also performed via QR-code markers.

2.3 Inspection Workflow

Upon entering the inspection area, engineers open the client on either an iPad or a HoloLens 2 and scan an on-site QR-code marker. After detection, the system loads the corresponding MEP model for that area and displays it as an interactive 3D model view. This model view is synchronised with the engineer's viewpoint: as the engineer turns or moves, the model rotates and updates accordingly, so that the model is always shown from the same viewing direction as the current on-site view. On the iPad, the interactive 3D model is shown on the right side of the screen. On the HoloLens 2, the model is presented on a central panel that follows the engineer's viewpoint as they move and look around. (Fig. 2a for iPad; Fig. 2b for HoloLens 2).

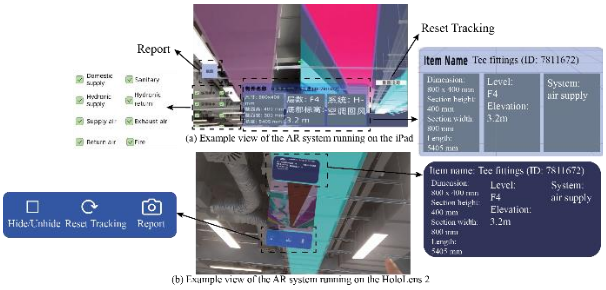

Figure 2 Screenshots of the AR system

The full model is used for browsing and target selection, while the AR overlay is shown only after a specific element is selected. To inspect a specific element, the engineer selects the target pipe or duct in the model using touch input on the iPad or a pinch gesture on the HoloLens 2. The selected element is highlighted in red in the model view. At the same time, the system displays an in-situ overlay of the selected element in the real-world view, allowing direct visual checking against the installed condition. As shown in Fig. 2, the iPad interface presents the live camera view with a highlighted overlay on the left, while the model view appears on the right. The HoloLens 2 provides the same interaction: the model is displayed on the central panel, and the selected element is overlaid in the user's view.

If an issue is found on a specific pipe or duct, the engineer selects the element and clicks the report button. A new window then opens, showing an on-site screenshot with the selected element overlaid (Fig. 3). The engineer can add notes to describe the issue. After the inspection is completed, all reported issues are automatically compiled into a single report.

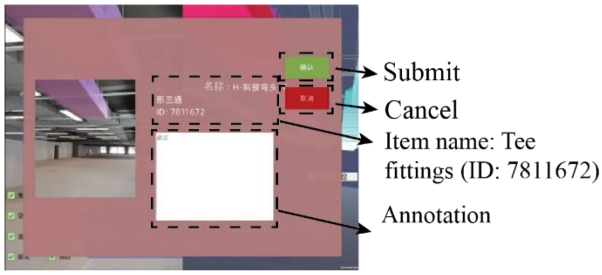

Figure 3 Example screenshot of the issue reporting window

3 On-site Evaluation

3.1 Site Description

The on-site evaluation was conducted on the fourth floor of a commercial office building project under construction. At the time of testing, the main structure had been completed, and the fourth-floor MEP installation had already been finished and set up as a mock-up area. The project adopted an open-ceiling design, so pipes and ducts were exposed without suspended ceilings, allowing clear visibility for inspection. Construction activities on this floor were paused during the evaluation, and the test area was considered safe and free of on-site operational risks.

Figure 4 Site photo of the evaluation area

3.2 Evaluation Setup

Table 1 summarises the evaluation setup. All participants were recruited from the construction project to ensure a realistic evaluation under an engineering context. A total of 91 participants took part in the field evaluation, including MEP engineers, foremen, BIM engineers, supervisors, and project management staff. Participants were randomly assigned to three groups: a 2D drawing baseline group (D, n=30), an iPad BIM+AR group (I, n=31), and a HoloLens 2 BIM+AR group (H, n=30). The participants' ages ranged from 20 to 58 years (mean 37.3).

Two representative on-site MEP inspection tasks were designed: an elevation verification task and a spatial relationship verification task. The elevation task focused on locating a specified pipe and reading its elevation-related information, which represents a routine site check. The spatial relationship task was more complex. Two target pipes were first indicated on site, and participants were asked to determine their intended spatial relationship (e.g., which pipe is above, below, in front of, or behind) and to report key attributes for each pipe (e.g., system type, such as supply or return). Both tasks were defined through discussions with on-site engineers and reflect common inspection activities. The first task focuses on checking pipe elevation, and the second on verifying that the pipe routing and spatial arrangement match the design.

All participants completed the two tasks (the elevation task and the spatial relationship task) using their assigned tool (2D drawings, iPad, or HoloLens 2). Task order was randomised. Each task was repeated three times at three different pipe locations, yielding six trials per participant.

Table 1 Summary of the on-site evaluation design

	Description
Task setup	Elevation task: locate the specified pipe and read its elevation. Spatial relationship task: identify the component attributes and determine their relative positions (above/below, left/right, front/behind).
Groups	Group D: 2D drawings (30 participants) Group I: iPad (31 participants) Group H: HoloLens 2 (30 participants)
Participants	Age 20-58 years (mean 37.3); MEP related position from the building project.
Data Collection	Completion time and answer accuracy

For each trial, the experimenter first pointed out the target pipe(s) on site and stated the question according to the assigned task (elevation or spatial relationship). After confirming that the participant clearly understood the target pipe(s) and the question, the experimenter gave a start signal. Only then could the participant begin using the device (or consulting drawings for the baseline group). When the participant had obtained an answer, they announced that they were ready to respond. At that moment, they were not allowed to continue operating the device or viewing drawings. The experimenter then recorded the response and confirmed the answer with the participant. The same procedure was followed for all trials. After completing three trials of the first task, the participant proceeded to the other task and completed the remaining three trials.

For each trial, task completion time and accuracy were recorded. Task time was measured from the start signal to the moment the participant indicated they were ready to answer. Before timing began, the experimenter only indicated the physical target pipe onsite, and participants were not allowed to view either the drawings or the AR interface in advance. Once the trial started, participants used their assigned tool to identify the corresponding pipe and retrieve the required information. Therefore, the recorded completion time included both element identification and information retrieval. This procedure was designed to ensure a fair comparison by keeping the physical inspection target consistent while evaluating the efficiency of drawings and AR in supporting these tasks.

This experiment was approved by the ethics committee of Tsinghua University (Approval No. THU-

04-2025-1119).

3.3 Data Analysis

The task completion time was computed as the mean of the three trials for that task. The task accuracy score was computed as the total number of correct answers across the three trials, resulting in a discrete score ranging from 0 to 3 per task.

For completion time, group differences were examined separately for each task. Normality was assessed for each group (Shapiro–Wilk). If normality was satisfied for all groups, a one-way ANOVA was conducted; otherwise, a Kruskal–Wallis H test was used. When the overall test was significant, a Dunn's post-hoc test was performed for pairwise comparisons. Bonferroni correction was applied to adjust p-values for multiple comparisons.

For task accuracy (0–3), which is a discrete outcome, differences between methods were examined using pairwise contingency table tests for each task. Because some cells could have small expected counts, Monte Carlo p-values were used. Bonferroni correction was applied to adjust p-values across the three pairwise comparisons (D vs. I, D vs. H, and I vs. H).

4 Results

4.1 Completion Time

Figure 5 compares the completion times across the three groups for the two tasks using boxplots. For the elevation task, both the iPad and HoloLens 2 conditions significantly reduced task completion time compared with the drawing-based baseline, indicating that BIM-integrated AR facilitates faster access to relevant on-site information. The average completion time was 24.0 s for the drawings, 7.9 s for the iPad, and 8.6 s for the HoloLens 2. No significant difference was found between Group I and Group H for this task.

For the spatial relationship task, which is more complex, the time advantage of Group H was not observed. The average completion time for the drawings was 25.3 s. The iPad condition still significantly reduced completion time (average = 16.7s), whereas the HoloLens 2 condition, although showing a lower mean time (16.3 s) than the drawing-based group, did not reach statistical significance. Field observations suggest that participants in the spatial task often spent substantial time selecting the target pipe within densely installed MEP systems, which increased interaction overhead, particularly on the head-mounted device.

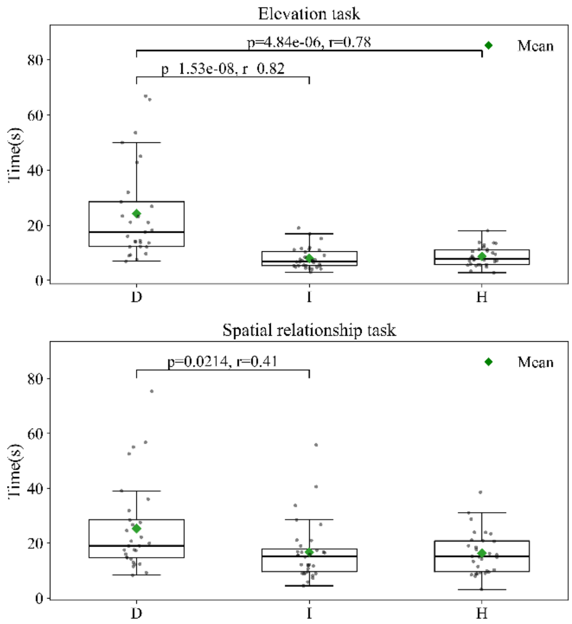

Figure 5 The boxplots of task completion time

4.2 Task Accuracy

Figure 6 compares task accuracy across the three groups.

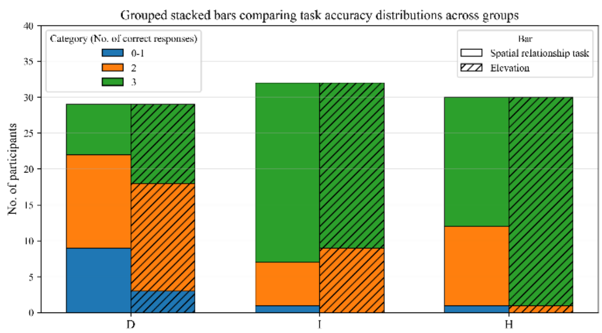

Figure 6 Bar chart of the task accuracy

For the elevation task, Group H achieved significantly higher accuracy than Group D ($p = 6.0\times10^{-5}$) and Group I ($p = 0.040$), and Group I also outperformed Group D ($p = 0.0287$). The higher accuracy of Group H relative to Group I is consistent with its more stable tracking: under the iPad condition, occasional model drift can cause participants to believe they selected the target pipe, even though they actually selected an adjacent segment, thereby reducing accuracy.

For the spatial relationship task, both Group I and Group H achieved significantly higher accuracy than Group D ($p = 0.00012$ and $p = 0.00846$, respectively), while Group I and Group H did not differ significantly ($p = 1.00$).

5 Discussion

The results indicate that integrating AR with BIM can effectively improve both the efficiency and accuracy of on-site MEP inspection. The observed time savings are largely attributable to AR-enabled in-situ visualisation, which reduces the time required to locate and identify target components in dense MEP environments—an advantage also reported in prior AR-based assembly and inspection studies [14, 15]. In terms of accuracy, linking BIM metadata to each pipe provides more reliable and centralised information retrieval: once the correct component is selected, the associated information is consistently retrieved from the BIM database, whereas paper drawings often distribute relevant information across multiple views and annotations. Collectively, these findings support the practical value of AR–BIM integration for routine on-site MEP inspection.

The comparative results further provide guidance for future deployment strategies. HoloLens 2 demonstrated that highly accurate inspection is achievable with current head-mounted AR technology; however, its interaction burden can increase task time, and prolonged use introduces practical constraints such as limited battery life and device heating, which may hinder continuous site operations. In contrast, tablet-based AR appears better suited to high-frequency inspection workflows. Tablets offer more efficient touch-based selection in congested pipe networks and typically provide longer operating time in field conditions. Nevertheless, the main limitation observed for tablets is tracking robustness, which can directly affect selection accuracy when model alignment drifts. Improving tablet tracking performance through enhanced sensors, more robust visual–inertial algorithms, or hybrid localisation strategies will be critical for reliable AR–BIM inspection.

Although the experiment was conducted in a real construction environment, it could not fully represent actual site conditions because all activities in the test area were paused during the experiment. Ongoing construction work could affect task completion time due to factors such as noise and interruptions. These influences may also affect participants using traditional 2D drawings and AR applications differently, which warrants further investigation in future research.

During the test, the iPad occasionally lost tracking and registration, whereas the HoloLens 2 remained relatively stable. This paper does not investigate the impact of tracking and registration performance on inspection outcomes; instead, it focuses on task performance with AR applications operated under stable, controlled conditions. Future studies could further examine this issue by conducting tests under different lighting conditions or tracking environments.

Only two inspection tasks were examined, which cannot represent the full MEP inspection process in practice. For tasks such as tolerance checking, inspectors would still need to obtain information from the prototype and then perform manual measurements on site. In addition, only task completion time and accuracy were evaluated in this study. Future research should include a wider range of inspection tasks and additional quality-related metrics.

Beyond MEP inspection, the same AR–BIM approach can be extended upstream to support pre-installation planning. For example, before MEP installation begins, AR can be used to preview routing, verify spatial clearances and constructability, and communicate installation intent across trades in the actual site context, potentially reducing clashes, rework, and coordination cycles. Future studies should further validate the feasibility of this extension through on-site testing.

6 Conclusion

This paper presented a BIM-integrated AR prototype that brings MEP model geometry and component attributes to the construction site and supports a closed inspection loop from on-site checking to structured issue reporting and BIM update. The system was deployed on both an iPad and a HoloLens 2 and evaluated in a real construction setting.

This paper provides field evidence that integrating BIM with AR can improve the efficiency and accuracy of on-site inspection compared with conventional drawing-based practice. The findings also reveal practical limitations and point to directions for improving system design and deployment in real construction environments. Beyond MEP inspection, the proposed workflow and lessons learned offer a useful reference for extending BIM–AR approaches to a wider range of construction-stage tasks and application scenarios.

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