



AUGMENTED REALITY FOR ENHANCED INSPECTION OF SECONDARY BUILDING COMPONENTS IN HEALTHCARE FACILITIES: A CASE STUDY

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Abstract

Healthcare facilities require strict safety and efficiency standards, yet secondary building components are often overlooked during handover. Existing methods like laser scanning and redlining are time-consuming and inadequate for inspecting secondary components. This article explores using Augmented Reality (AR) in inspecting secondary components in healthcare construction projects. A case study in a UK project is presented, where secondary components in patient rooms are inspected. The inspection identified 25 deviations from design, highlighting the effectiveness of AR in enhancing inspection accuracy and efficiency. The study recommends integrating AR into existing inspection workflows and further research on scalability, cost-benefit, and standardized protocols.

Introduction

The design and construction of healthcare facilities are complex endeavors, primarily focused on patient safety, comfort, and efficient care delivery. Sophisticated design, unique infrastructure requirements, and strict adherence to standards and regulations significantly contribute to this complexity (Choi et al., 2018). While primary building components often receive considerable attention during design and construction, secondary building components are equally critical during the operational stage. Elements such as partitions, doors, and windows substantially influence a building's environment and functionality (Adán et al., 2018). Secondary components linked to Mechanical, Electrical, and Plumbing (MEP) services—including sinks, toilets, and electrical outlets—are particularly vital for operations (Teo et al., 2022). Their strategic placement and arrangement significantly impact patient safety, accessibility, and infection control. However, inspecting these components against design specifications during handover is frequently overlooked and has received limited research attention to date (Adán et al., 2018; Seddighi et al., 2024).

Efforts to capture the as-built status of building objects have primarily focused on identifying and modeling large structural elements, such as walls, floors, and columns. For MEP systems, these efforts have centered on pipe

recognition and positioning, primarily using laser scanning and photogrammetry (Adán et al., 2018). These technologies rely on generating point clouds of built objects and updating design models accordingly (Mihic et al., 2023). Alternatively, redline markups is a predominant workflow where users use red pens to mark changes, corrections or annotations on printed drawings, indicating alterations to the original design, notes about specific objects, or feedback from project stakeholders (Reja et al., 2022). These methods struggle to capture smaller, variably shaped secondary building components (Wang et al., 2022).

Point cloud models generated from 3D laser scanning often have massive file sizes, requiring substantial data storage (Qu & Sun, 2015). Additionally, integrating point cloud models into BIM authoring tools significantly degrades software performance, even on high-end computers (UNDET, 2023). Furthermore, point cloud models lack a shared coordinate system with design models, necessitating manual alignment using "Move" and "Rotate" commands—a process that may compromise the accuracy of the resulting as-built model (Hitech BIM Services, 2022). Another limitation is that laser scanning cannot be configured to ignore minor deviations within permissible tolerances, even when such variations have no impact on as-built model quality (Mirzaei et al., 2022). These challenges apply universally, whether using static (terrestrial), mobile, or airborne laser scanning. On the other hand, redlining workflow is time-consuming, error-prone, and incapable of accurately describing changes made onsite, resulting in time-inefficient monitoring (Bosché et al., 2014).

However, it is well established that AR is expected to play a pivotal role in streamlining workflows in the construction and handover stages (Wang et al., 2013). The integration between AR and BIM extends the scope of BIM to be used in construction sites by enabling access to interactive full-scale design models, bridging the gap between the site and the office (Chai et al., 2019; Nikolic D et al., 2019). It is well-documented that AR is most beneficial for applications in the construction stage (Chen & Xue, 2020; Sidani et al., 2021). Several studies indicated that AR is most beneficial for post-installation

activities such as as-built modelling and quality control (Amin, Mills, et al., 2023). As such, this research aims to evaluate the effectiveness of AR in inspecting secondary building components in healthcare construction projects. Effectiveness here refers to the ability to deliver the intended result in real-world condition. To that aim, two research questions are derived:

Q1) How does the integration between BIM and AR address the current challenges of inspecting secondary building components in healthcare construction projects?

Q2) How does the AR-based inspection process compare to laser scanning and redlining in terms of accuracy and time efficiency?

BIM-based AR

Augmented Reality (AR), an emerging development in visualization technologies, presents significant opportunities for the construction industry (Amin, Mills, et al., 2023). AR enables the real-time overlay of interactive digital objects onto physical environments (Azuma et al., 2001). Recognizing its potential, researchers have primarily focused on AR applications during the construction phase, where it demonstrates the greatest promise (Sidani et al., 2021). Key use cases include on-site task guidance, worker training, information retrieval, layout visualization, progress tracking, and quality control (Chen & Xue, 2020; Nassereddine, Hanna, et al., 2022).

The integration of Building Information Modeling (BIM) with AR holds particular transformative potential for construction workflows (Farghaly et al., 2023). By superimposing full-scale BIM models onto physical sites, AR facilitates enhanced stakeholder collaboration, real-time issue resolution, and improved decision-making. Additionally, AR supports efficient quality control by enabling visual comparison between planned designs and as-built structures (Sidani et al., 2021).

AR-based quality control supports inspections by overlaying design models onto as-built structures to detect defects and deviations. Liu et al. (2021) and Wen and Kang (2014) integrated UAVs with AR to facilitate quality inspection sessions. Zhou et al. (2017) discussed the feasibility of using AR to detect tunnel segment displacement from the design model and indicated that AR could be used as an effective and cheap way to detect deviations onsite. Mirshokraei et al. (2019) conducted a case to support the inspection of structural objects using AR, indicating that AR led to reductions in defects, rework and improved access to information. García-Pereira et al. (2020) developed a prototype for geolocated annotations, enabling collaborative inspections. However, AR research in quality control has focused on large building components and software development, with limited adoption in construction (Davila Delgado et al., 2020).

Despite AR's potential, its adoption in the UK construction sector is low, estimated at 1.5 out of 5, where 5 represents full adoption (Davila Delgado et al., 2020). Practical implementation remains poorly understood, with research often focusing on software development, such as creating prototypes and experimenting with localization techniques (Davila Delgado et al., 2020). Studies predominantly address technical challenges like 3D model localization and accuracy evaluation (Amin, Mills, & Wilson, 2023; Nassereddine, Schranz, et al., 2022). Industry-focused AR case studies are needed to bridge the gap between theory and practice (Palmarini et al., 2018). This paper addresses this gap by presenting a real-world case study on using AR to inspect secondary building components in healthcare construction projects.

Methodology

This research employs a case study design to explore AR's application for inspecting secondary building components. The methodology aims to provide an in-depth understanding of AR's practical challenges, benefits, and limitations in this context. The study was conducted in four phases: (1) case selection, (2) preparation, (3) inspection and data collection, and (4) analysis, and reporting. Each phase is detailed below.

Case Selection

The first phase involved identifying a suitable case and preparing the site for inspection. Selection criteria included geographical accessibility and project stage. The chosen project was a UK healthcare facility nearing completion. Patient rooms were selected as sample spaces due to their variety of secondary building components, which are critical for patient safety and comfort. The AR-based inspection aimed to identify deviations from the design. For confidentiality, the project and contractor names are not disclosed.

Preparation

The AR platform used is XYZ Reality's AR Cloud platform. The main hardware components are the ATOM which is an engineering-grade AR headset specifically designed for construction projects, a pointing device used for interacting with objects and tracking beacons to provide positional accuracy while tracking the headset during inspection (Figure 1). The hardware is integrated with a cloud service used for storing and sharing captured data (XYZ Reality, 2022). The AR platform is integrated with the BIM platform using plug-in installed on the client's BIM authoring tool.



Figure 1: The AR headset (ATOM), the pointing device, and the tracking beacons.

Table 1 provides more details about the technical specifications of the AR platform following the PIVCAT structure, which breaks down AR platforms into six key functions: **P**ositioning, **I**nteraction, **V**isualisation, **C**ollaboration, **A**utomation, and **i**ntegra**T**ion (Amin, Mills, & Wilson, 2023).

Table 1: XYZ Reality AR platform specifications

Key Function	Description
Positioning (P)	A hybrid positioning system, employing outside-in tracking using external optical sensors for positional tracking, and inside-out tracking using cameras and sensors inside the headset to allow for vision-based tracking when the headset loses line of sight to the optical sensors. The accuracy of the system has been estimated to be around 2-7 millimeters in normal in-door lighting condition.
Interaction (I)	A tangible UI in the form of a pointer that casts virtual rays to select and interact with digital elements.
Visualization (V)	An Optical-See-Through visualization system, with visibility customization features including hide, show, control transparency and brightness of digital elements.
Collaboration (C)	The platform allows for the different modes of collaboration including co-located or remote and synchronous or asynchronous, depending on the availability of internet connection onsite.
Automation (A)	No automation functionalities were used during inspection.
Integration (T)	The platform can be integrated with BIM authoring tools like Autodesk Revit.

Inspection and Data Collection

The inspection process began by identifying spaces to inspect and creating 'Inspection Volumes' which are information-rich 3D models of these spaces. Using the XYZ plugin, these volumes were downloaded to the AR headset via the AR cloud platform. Onsite, the inspector superimposed and aligned the Inspection Volume to the physical space. Visual checks were conducted to identify discrepancies in location, size, and material specifications of secondary components compared to the design model. Detected deviations were captured and uploaded to the AR cloud platform for analysis and discussion. Data collection occurred over one week, with inspectors using the AR system. The data collected included:

- An image of the observation highlighting the deviation by showing the design model overlaid on the physical environment.

- A description of the issue, indicating the discipline and category of captured elements.
- The time and room name in which the observation was captured.

Analysis

The collected data were analyzed using a mixed-methods approach. Captured images were visually analyzed to describe deviations and identify involved elements. These observations underwent content analysis to provide quantitative insight into the outcome of the inspection process.

Ethical Considerations

Arrangements were made with the area manager to minimize the AR device's view of workers, protecting their identities. When unavoidable, photo editing tools were used to blur workers' faces and hide company names.

Results and Discussion

Onsite, the AR headset uses computer vision and depth-sensing technologies to scan the environment and identify plane surfaces like walls. The inspector aligns the design model to the physical space by matching three plane surfaces from the model to corresponding physical surfaces in the inspection area. The AR headset recognizes these surfaces when the inspector taps three points on them using the pointing device (Figure 1). Typically, these surfaces include the floor and two walls. The inspection was conducted in six ensuite patient rooms.

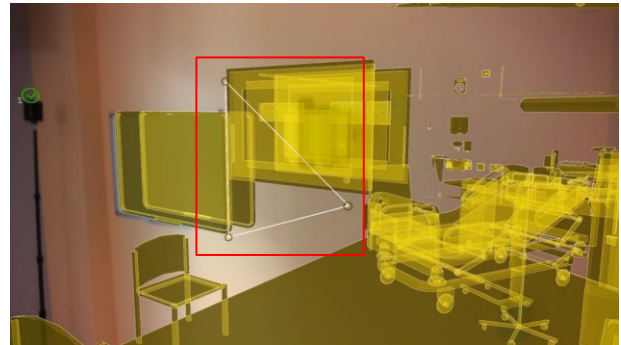


Figure 1: identifying three points to define the surface of the physical wall

Inspection Result

The AR-based inspection identified a total of 25 deviations from design in four patient rooms, representing an area of around 50 square meters (Table 2). The bar graph in Figure 2 presents the frequency of deviations identified in secondary building components across four engineering disciplines within the inspected area. Plumbing exhibited the highest number of deviations with a count of 15, followed by Electrical with 7 while Mechanical recorded a lower count of 2. This highlights the disproportionate distribution of deviations among the

disciplines, highlighting plumbing as the area with the most significant quality control challenges. The bubble chart in Figure 3 shows the distribution of components with plumbing fixtures such as sinks, grab rails scoring the highest number of deviations.

Table 2: Descriptions, component discipline and category in captured observations

Observation	Component Discipline	Component Category
Lighting Fixture location is different from the design model.	Electrical	Lighting Fixtures
Sprinkler location is different from the design model.	Plumbing	Sprinkler
Sprinkler location is different from the design model.	Plumbing	Sprinkler
Air terminal location is different from the design model.	Mechanical	Air Terminal
Toilet type is different from the design model.	Plumbing	Plumbing Fixtures
Toilet room type and arrangement is different from the design model.	Plumbing	Plumbing Fixtures
Toilet room type and arrangement is different from the design model.	Plumbing	Plumbing Fixtures
Grab rail is not installed as per the design model.	Plumbing	Plumbing Fixtures
Toilet room type and arrangement is different from the design model.	Plumbing	Plumbing Fixtures
Socket location is not as per the design model.	Electrical	Speciality Equipment
Air terminal type and orientation are not as per the design model.	Mechanical	Air Terminal
Socket location is not as per the design model.	Electrical	Electrical Fixtures
Sink type and arrangement is different from the design model.	Plumbing	Plumbing Fixtures
Socket location is not as per the design model.	Electrical	Plumbing Fixtures
Sink type and location is not as per the design model.	Plumbing	Plumbing Fixtures
Sockets are not installed as per the design model.	Electrical	Electrical Fixtures
Lighting Fixture size is not as per the design model.	Electrical	Lighting Fixture
Air dryer slightly shifts from the location in the design model.	Plumbing	Electrical Fixtures
Grab rail type is not as per the design model.	Plumbing	Plumbing Fixtures

Sink type and arrangement is different from the design model.	Plumbing	Plumbing Fixtures
Socket and support locations are different from the design model.	Electrical	Plumbing Fixtures
Sink type and arrangement is different from the design model.	Plumbing	Plumbing Fixtures
Sink type and arrangement is different from the design model.	Plumbing	Plumbing Fixtures
Grab rail type is not as per the design model.	Plumbing	Plumbing Fixtures

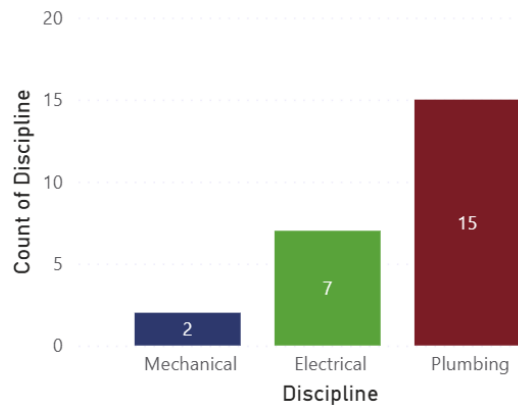


Figure 2: Number of deviations in each discipline

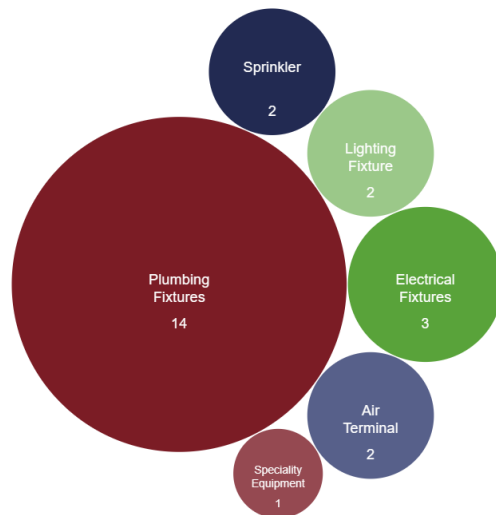


Figure 3: Number of deviations in each component category

Since the scope of this paper does not allow discussing each issue in detail, the next sections provide in-depth analysis of interesting captures and highlight the effectiveness of AR over alternative methods in inspecting secondary building components.

Significance of Captured Issues

In recognition of the patient room layout's crucial role in patient safety, efforts have been made to integrate fall prevention measures into building design. While the strict

adherence to standards are spelled out, the architect is often bypassed by subcontractors, especially in secondary building components (Symons, 2021). AR simplifies detecting and reporting such deviations promptly. Figure 4 shows a deviation in grab rail placement between design and actual installation. The AR overlay clearly highlights the deviation, making it easily identifiable for inspectors. AR enhances the inspection process, enabling better assessment of permissible deviations.



Figure 4: Deviation in the location of the toilet room grab rail

The strategic placement of sockets and lighting in patient rooms is crucial for accessibility and comfort. Proper positioning of electrical outlets supports medical equipment, personal devices, and mobility aids, enhancing independence and reducing fall risks. Detecting deviations in these components using traditional methods is challenging. Figure 5 shows a deviation in the location of an electrical outlet beside the patient bed using AR. The detection of this deviation, albeit small, allows for the future investigation of its impacts during the operation stage, helping design teams taking more informed decisions regarding such deviations in future projects.



Figure 5: Deviation in the location of the electrical outlet

Advantages of AR Over Alternative Methods

The use of AR in the context of inspection of secondary building components has proven to be valuable for

effectively identifying the deviation from design intent. By overlaying the original design of the secondary component onto the real-world environment, AR enabled a direct visual comparison onsite between the intended and actual placement and material of the component. The measurement and markup tools featured in the AR platform enabled quantifying the amount of deviation and making comments for future discussions. This approach eliminates the need for creating point clouds and comparing them with design models or creating redline markups to describe changes made during installation. Point cloud models often have massive file size and require large data storage. In addition, working with point cloud models in BIM authoring tools has a significant negative impact of the performance of the tool even with high-end computers.

Using AR, the detection of discrepancies happens onsite, not in the office, hence saving a significant amount of time and effort compared with laser scanning. This approach facilitates immediate identification and communication of issues, discrepancies, and progress updates. Site personnel can use AR to capture precise data and visual evidence, which can be instantly shared with the office team, ensuring that any concerns are addressed promptly and accurately. This enhances the feedback loop between the site and the office, allowing for collaborative issue resolution.

AR allows identifying issues and creating discrepancies while onsite which in turn has provided the ability to decide what is major and what is minor onsite. This is not applicable in point cloud and redlining workflows, where the user begins observation after processing the resulting point cloud and manually inserting it into the design model and conducting the analysis.

AR allows the inspector to focus on specific elements by isolating them or changing their appearance while onsite. This has helped capturing AR images that only showed the elements of concern and clearly described the issue with these elements. Again, this is not applicable in point cloud and redlining workflows, where the user must scan the whole surrounding environment and then compare the resulting point cloud with the design model.

Addressing Research Aim and Questions

The existing literature underscored the transformative potential of AR in construction, particularly in streamlining workflows during construction and handover stages (Wang et al., 2013). AR has been widely recognized for its utility in post-installation activities, such as as-built modeling and progress tracking, where it enhances accuracy and efficiency (Amin, Mills, et al., 2023). However, its application in inspecting secondary building components, especially in healthcare construction, remained underexplored. This research addressed this gap by evaluating AR's effectiveness in this context.

The first research question aligns with studies emphasizing the integration of AR with BIM, i.e. BIM-based AR, to enhance post-installation activities such as quality control, as-built modelling and progress tracking. This study has demonstrated AR's real-time visualization capabilities, complementing BIM's ability to provide detailed digital representations of building components, and creating a synergistic effect that can improve inspection processes. The practical steps of model alignment, localization, visual inspection, and reporting were presented through four inspection phases: case selection, preparation, inspection and data collection, and analysis and reporting. The inspection process successfully identified 25 design deviations in six patient rooms, predominantly in plumbing components. The majority of deviations represented components in locations different from those in the design model. The findings demonstrated how AR simplifies deviation detection and reporting, ensuring compliance with design standards, and resulting in an efficient inspection process.

The second research is concerned with how effective AR is inspecting secondary building components, compared with point cloud and redlining workflows which are the predominant methods for as-built inspection. Unlike laser scanning, which requires capturing and processing point clouds, which have massive file size and are computationally demanding, AR overlays digital models onto the real-world environment, enabling immediate comparison. Additionally, AR facilitates instant decision-making by enabling inspectors to identify and classify issues onsite, improving efficiency compared to point cloud workflows. AR also enhances communication by allowing site personnel to share visual evidence instantly with office teams, fostering a faster feedback loop. Furthermore, AR enables isolating specific elements, improving focus and clarity in issue documentation, whereas laser scanning captures the entire environment before analysis. On the other hand, AR eliminates the need for redline markups, as AR's measurement and annotation tools allow direct documentation of discrepancies.

Limitations

This study is limited by its reliance on a single case study, which may restrict the generalizability of its findings. Furthermore, the accuracy of AR-based inspection depends on the quality of model alignment, which can be affected by lighting conditions and tracking limitations. The accuracy of model alignment may vary depending on the AR platform as well, and so different results are expected when using different localization techniques. Additionally, while AR facilitated real-time deviation detection, the study does not evaluate its effectiveness in resolving issues beyond documentation. Future research should include multiple case studies across various project types to provide a more comprehensive assessment of AR's role in construction inspection.

Conclusions

This study demonstrated AR's transformative potential for quality inspections of secondary building components in healthcare construction. By superimposing digital models onto physical spaces, AR enabled real-time, on-site identification of design deviations, improving inspection accuracy and efficiency. The case study revealed AR's effectiveness in detecting discrepancies in component placement and material specifications - critical factors for patient safety and operational performance. Unlike conventional methods, AR facilitated immediate documentation and communication of issues, establishing a dynamic feedback loop between field and office teams. This real-time interaction reduced project delays, minimized errors, and enhanced collaborative decision-making.

The findings underscored the importance of AR adoption in construction, particularly for complex healthcare environments where strict compliance with design standards was essential. As AR technology continued to evolve, its integration into construction workflows promised to effectively bridge the gap between digital planning and physical implementation, yielding more reliable and efficient project outcomes.

Further research is needed to explore AR's scalability across different project sizes and spaces, conduct long-term cost-benefit analyses, and develop standardized protocols for data capture and analysis. By addressing the limitations of traditional methods, AR empowers construction professionals to deliver higher-quality healthcare facilities that prioritize patient safety, comfort, and operational efficiency.

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