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Field Testing of Mixed Reality (MR) Technologies for Quality Control of As-Built Models at Project Handover: A Case Study

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Current as-built BIMs generated during design and construction and delivered to owners at project handover do not fulfill all FM needs. To provide value, an FM-Capable BIM is required that is optimized for operations and maintenance. Two of the requirements of an FM-capable BIM is that it serves as a central repository for accurate, complete, and reliable data, and it provides accurate and complete representation of building components and systems. This paper reports on a collaborative project to evaluate the usability and effectiveness of the Hololens with the VisualLive HoloLive platform to test the accuracy and completeness of model graphical and non-graphical information. A Navisworks as-built BIM of the mechanical room of a classroom building was used. The paper also outlines current Mixed Reality (MR) features, compares two MR platforms, HoloLive and Trimble Connect, and provides future research direction. Results indicated that the usability and effectiveness of MR technologies are adequate to verify model data and test quality of the BIM graphics. However, the users had difficulties with typing, dependency on WiFi signals, visibility of distant objects, objects in low lighting areas and objects with dull colors. Concerns regarding the wearability and safety of the glasses were highlighted.

Key Words: Mixed Reality, Operation & Maintenance, Quality Control, BIM, As-Built

Introduction

Data and information captured and embedded in a Building Information Model (BIM) can support and benefit operation and maintenance. What is being realized is that current BIM deliverables generated during design and construction, and provided to owners during project handover, generally do not fulfill facility management (FM) needs. Project handover is the incremental process of transferring or delivering the physical building as well as all data and information associated with its design and construction from the project team to the facility owner. Handover is a process conducted through a period of transition and is not a date. Models delivered at project handover are not optimized for operation and maintenance (O&M). The root of the problem is that majority of facility owners cannot articulate their BIM requirements in the language of BIM and design and construction teams continue to guess what is required of the scope, syntax, and format of the information that facility managers require or need. For the BIM deliverable to provide value, an FM-Capable BIM is required that is optimized for operations and maintenance. An FM-Capable BIM is a customized or configured model that provides the needed critical operation and maintenance information, solve operational challenges, and improve safety and efficiency in various ways.

FM Capable BIM

Based on their combined work experiences and research investigations in the area of BIM and its applications to construction, the authors define four requirements or characteristics that need to exist to render the as-built model capable of supporting FM requirements

1. Model is data-centric: BIM models can serve as a central repository of relevant and necessary data and information to allow facility managers operate and maintain their facilities efficiently and effectively. Data must be accurate, complete, and reliable.
2. Model is an accurate and complete representation of building components and systems. In other words, the model geometry must match actual construction and be at the appropriate Level of Development (LOD) (Latiffi et al., 2015) and Level of Accuracy (LOA) (USIBD Level of Accuracy (LOA) Specification Guide, 2014) required.
3. Model is systems-centric: The model should be customized with operationally useful and meaningful viewpoints and search sets that display building components linked to a specific system (e.g. AHUs, fans, ducts, VAVs, valves and diffusers belonging to the Supply Air system). This can assist facility managers in making critical decisions and improving the O&M of facilities.
4. Model is directly linked with the facility information management system (e.g. Computerized Maintenance Management System CMMS) to allow forbi-directional information update.

This paper uses a case study and focuses on testing the quality of as-built handover BIMs from the perspective of the first two requirements: accuracy and completeness of graphical and non-graphical information.

Use of Augmented Reality (AR)/Mixed Reality (MR) to Review BIM Models

Augmented reality (AR) glasses display real-time simulated 3D model aligned with the real environment. By displaying the BIM against the real world, model graphics and data can be checked and verified. Examples of use cases of AR in construction industry are assembly and prefabricated construction (Davila Delgado et al., 2020; Cheng et al., 2020). Previous studies have highlighted the beneficial aspects of using Augmented Reality (AR) technologies for enhancing facility operation and maintenance (Palmarini et al., 2018). The differences between VR and AR are their presented background which in VR is the computer-generated graphic while in AR is the real environment (Davila Delgado et al., 2020; Cheng et al., 2020). Compared to AR glasses, Mixed reality (MR) glasses allows interaction among human, physical and virtual objects including use of gestures. AR/MR can use both head mounted displays and handheld devices such as mobile applications. Mixed Reality technologies were first introduced as a 3D head mounted display in the 1960s by Sutherland (Cheng et al., 2020). The construction industry has been slow in adoption of these technologies compared to other sectors due to expensive hardware and training, skill shortage, lack of standards for data exchange, etc. (Davila Delgado et al., 2020). Various researchers have explored the use and implementation of the technologies and tested features for aligning models with reality and verification of model graphical and non-graphical data.

Delgado et al. (2020) compared different tracking methods of marker-based and marker-less methods in terms of accuracy. Based on their results, although marker-based methods are more accurate and consistent compared to marker-less methods, they require placing the trackers through the building/facility. Their results indicate that marker-less methods are best for detailed objects. They recommended using a combination of both methods for better results. Machado and Vilela (2020) analyzed the different tracking technologies for AR and concluded that percentage use of GPS/GIS and fiducial markers have been the highest due to low cost and ease of use. However, their performance depends on external factors such as climate and sunlight. Therefore, they highlighted the importance of addressing higher precision and occlusion of AR devices used for construction sites. Gomez-Jauregui et al. (2019) identified the tracking challenges and image processing approaches as main reasons for AR accuracy limitations and proposed a method for addressing the overlaying discrepancies by measuring the discrepancies as well as filtering sensor signals. Neges et al. (2017) demonstrated the challenges associated with using natural markers for AR localization presented in their previous study (Koch et al., 2014) and proposed an alternative method. They believe that natural markers are not useful tools for estimating the position and orientation of users if visual markers are unavailable, if the same markers are used at various locations, and if the signs emit lighting. To address the issues with natural markers, they proposed a method based on Inertial Measurement Unit and visual live video. However, their proposed solution has limitations such as manual start point selection. The QR codes can be used to address their limitation.

Delgado et al. (2020) reviewed the applications of AR in different stages and aspect of construction including planning, scheduling, progress monitoring, safety, and operation. Their results indicated that AR allows access to contextual information as well as information related to the location of the assets. On the other hand, they highlighted the interoperability issues as one of the challenges limiting the AR adoption. Carneiro et al. (2019) proposed an approach using AR glasses to allow users to visualize information related to their energy consumption in an office setting. Such approach increases user understanding of the connections between building systems as well as their impact on energy consumption. Wang and Piao (2019) used context aware AR glasses in their proposed prototype to provide information and guide the maintenance process supporting decision making. They believe that using AR glasses will increase the productivity of users by providing real time access to the information. Del Amo et al. (2018) proposed a framework for integrating AR into maintenance procedure to provide access to information. They investigated the information types and formats for different maintenance processes in order to enhance performance. Their framework can be used as a basis for developing AR systems. Ahmed (2018) highlighted the enhanced information access on construction sites using AR leading to delays reduction. The researcher indicated that having access to precise information reduces construction cost and time. However, lack of experts for using AR was mentioned as a limitation for AR adoption. Behzadi (2016) explored beneficial aspects of using AR technology in construction industry. The researcher demonstrated the positive impact of AR on costs by providing information to the project managers on-site to support their decision-making process. However, the size of the building models was highlighted as a barrier for wide adoption of AR technologies. Gheisari et al. (2014) developed a system by integrating AR and BIM in order to help facility staff to access information and better locate the components and assets within the facility. They believe that their proposed system can decrease information overload leading to better performance in less amount of time. They highlighted the importance of user-centered design as well as information requirements in order to provide beneficial AR tools.

The next section provides a description of Mixed Reality tools and compares two platforms: VisualLive HoloLive and Trimble Connect. A case study section provides an overview of the academic building used for testing and reports on results. The paper concludes with a discussion on the need for further testing using a more detailed user-based assessment tool.

Tools Available in MR Platforms

Prior to field testing the MR technology, a comparison study was conducted between two mixed reality platforms running on the MS HoloLens: VisualLive HoloLive and Trimble Connect. The study looked at available features and tools provided by each platform. Hololive allows to view model graphics and information exported from Revit and Navisworks on the Hololens as well as other mobile devices (e.g. iPad). Trimble Connect is designed specifically for the HoloLens and currently only support models authored in Revit. Both applications are designed to support informed decision-making and model access is cloud-based. The following is a brief summary of tools that are characteristics of a mixed reality platform. Table-1 provides a listing of each tool and defines its availability in the VisualLive HoloLive and the Trimble Connect applications.

*Alignment***.** Spatial registration or alignment allows users to align the 3D model with the real environment. This provides accurate overlay of the model elements on the built components. Once aligned, the user can verify the accuracy of the model components against reality. Various alignment options available include plane, fine-tune, marker scan (e.g. QR codes), two-point placement, manual placement, and natural markers.

Viewing Data. Having access to information such as asset data is one of the beneficial aspects of using MR glasses on site. Such feature will provide access to accurate information in real time. User-defined data in software such as Revit (see figure 2) or Navisworks models can be exported and downloaded to the glasses.

Issues Report. When an issue is found on-site, it can be captured and sent to the office for further considerations. Issues can be captured by taking screenshots, attaching images, defining the priority of the issue, and adding descriptions. The issues created can be uploaded to Google Drive, OneDrive, BIM360, or ProCore. Another option is to directly assign an issue to a specific person by sending them an email.

Measurement. Measurement tool can be used to measure distances between two points in the model, in reality or between model and reality.

Multi-Person Collaboration. Co-located or remote collaboration provides the opportunity for the users to share views and collaborate while in the same location or when they are in different locations.

Layers. Creating different layers will give the option of hiding or unhiding parts of the models or a complete model (if multiple models are launched together). Such tool allows the user to filter parts of the model and highlight specific components.

Step by Step Instruction. Providing step by step instruction for the operators and displaying them on the glasses will support maintenance tasks and enhance productivity (Sanna et al., 2015; Yuan et al., 2008).

Route Guidance. This tool provides access to the location of the user. User location allows to display route guidance to find the location of the targeted asset (Wang et al., 2015)

Intelligent Fault Diagnosis. Connecting MR glasses to intelligent technologies such as sensors will provide real-time access to information to identify diagnosis (Dong et al., 2013; Wang et al., 2015)

The information provided in Table-1 was collected during testing the various tools using both platforms (Trimble Connect and HoloLive). Specific tools listed above (Natural Markers, Step by Step Instruction, Route Guidance and Intelligent Fault Diagnosis) and included in the "Other" column in Table 1, were additionally identified from review of literature cited.

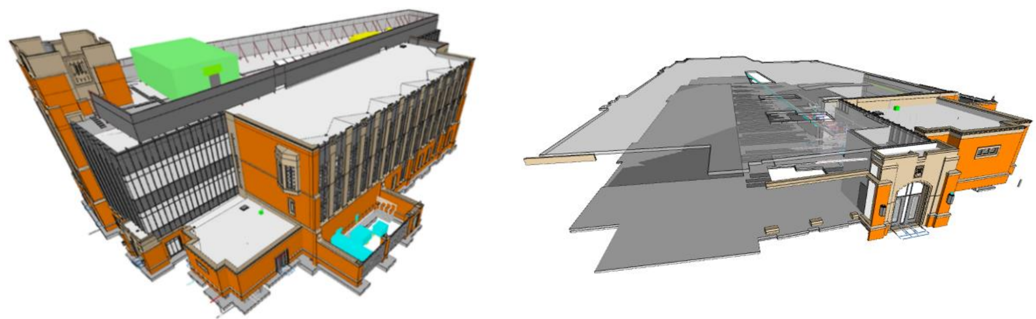
Table 1

Comparing tools among different applications

Tool	Trimble Connect	HoloLive	Other
Alignment			
Fine-Tune	x		
Manual		x	
Plane	x		
QR Code		x	
Two-Point		x	
Natural Markers			x
Viewing Data			
Revit Properties	x		
Navisworks Properties		x	
User-Defined Properties		x	
Issues Report			
Cloud		x	
Email	x		
Measurement			
Model to Model	x		
Real to Model	x		
Real to Real	x		
Any point		x	
Multi-Person Collaboration			
Co-Located Collaboration	x		
Remote Collaboration	x		
Layers			
Different Models	x		
Defined Layers		x	
Model Types Supported	Revit	Revit, Navisworks	
Step by Step Instruction			x
Route Guidance			x
Intelligent Fault Diagnosis			x

Case Study Methodology

The research team tested the use of the MS Hololens 1st Generation) with the VisualLive HoloLive platform to verify the accuracy and completeness of graphical and non-graphical information in as-built BIMs. A 3D Navisworks model of a three-story mixed classroom and labs building on the campus of a large academic institution was used for conducting this investigation. The mechanical room was selected as the test area. The model was provided by the facilities department of the academic institution. Figure 1 shows the as-built BIM model of the building and mechanical room located on the first floor.



(a) (b)

Figure 1. Navisworks As-Built Building Model (a) and First Floor Mechanical Room (b)

Five members of the academic institution's facilities department where invited to attend a 30-minute presentation providing a background on MR technologies, a quick demo of the HoloLens and the scope of the experiment. The research team and the invited staff then moved to the mechanical room for field testing.

The case study was conducted using the following steps:

1. Prior to field testing, the 3D model was configured for the HoloLens using the HoloLive application plugin. HoloLive was used because it supports the *.nwd Navisworks file format. To align the model with reality when uploaded to the glasses, two methods were chosen while in Navisworks: "Marker Scan" (QR code) and "Two Point Placement". Additionally, specific model data properties and values were selected using the "Quick Properties" feature of Navisworks and exported with the model graphics.
2. The model was uploaded to the cloud and imported to the HoloLens.
3. While in the mechanical room, the model was retrieved and aligned with reality using both alignment methods. The model was tested to make sure that alignment was accomplished successfully.
4. Various MR tools in the HoloLive platform were tested including measuring tools, overlay reality, data transfer and display capabilities, issue reports, etc. Figure 2a shows a facility staff member testing the HoloLens. Figure 2b illustrates the measuring tool of HoloLive software used to verify the accuracy of the as-built graphics with reality for a heat exchanger.

(a) (b)

Figure 2. Using the HoloLens with HoloLive Measuring Tool

5. The ease of use and learnability of the technology as well as the degree to which the workflow and technology were successful in producing the desired results were captured from verbal comments and feedback provided by the facility staff during the testing.
6. Hardware and software were evaluated using two criteria, usability and effectiveness. Usability is defined as the ease of use and learnability of the technology. Effectiveness refers to the degree to which the workflow & technology were successful in producing the desired results. These were captured by the research team and documented during the visit.

Summary of Results and Discussion

Table 2 summarizes the results of the two tested criteria.

Table 2

Summary of tested criteria

	Positives	Negatives
Usability	○ Easy to set up ○ Easy to align model with reality ○ Model alignment remained fairly stable ○ Quick AR Model Creation (typically)	○ HoloLens Ergonomic/ Long-term Use Concerns ○ Typing Issues ○ Wi-Fi availability ○ Field of View ○ Safety Concerns
Effectiveness	○ Proved effective as a general model check ○ Capturing images, issues, RFI's, observations, or punch list items ○ Measurement tool accuracy	○ Visibility Concerns (caused by reality) ✓ High elevation/ far away objects ✓ Line of sight ✓ Insufficient lighting ✓ Dark Colored objects ○ Visibility Concerns (caused by AR overlay) ○ Model element colors ○ Measurement Frustrations

From a *usability* perspective, once the model was downloaded to the glasses it was easy to setup and align. Alignment remained fairly stable within 30-40 ft from the origin point. The research team had concerns with wearability of the glasses for an extended period of time (more than 20-25 minutes) as well as typing, speech recognition, Wi-Fi availability, Hololens' field of view, and safety considerations. Typing with the HoloLens slow with clicker – choosing each letter one-by-one was a time-consuming and taxing process. The Hololens II, not used in this testing but tested at a later date, has modified its keyboard functionality and provided a much better user-friendly interface. Some users became uncomfortable and some may have experienced some dizziness and eye strain. Also, some users may have experienced sore arms because of air tapping on the Hololens' field of view for an extended amount of time. Speech recognition was inconsistent and affected by the loud noises in the mechanical room. Some HoloLive application features were highly dependent on a good Wi-Fi signal to perform certain tasks including loading models or uploading reports and images, which may become week or unavailable in certain building areas such as basement floors where mechanical rooms are usually located. The field of view prevented the full view of equipment or its context in tight areas and it also negatively impacted the images captured by covering more than what the user could see. There were also some safety concerns when using the glasses in congested areas such as mechanical rooms.

From an *effectiveness* perspective, the technology proved adequate to verify model data and graphics. Various features of the HoloLive platform allowed for capturing images and issues for sending RFIs or punch list items. However, images captured lost much of the 3D effect making it difficult to understand the images if they are later reviewed without markups. The measurement tool allowed various options and provided a good level of accuracy. The research team had concerns regarding visibility of distant objects, objects in low lighting areas (e.g. above ceiling), or objects with dull colors that matches colors of corresponding elements in the model. Coloring the model elements with a different color than their actual color as well as turning down the headset opacity settings helped with addressing the visibility concerns to some extent. While the measurement tool provided different measurement options, the team experienced some frustrations when trying to overlay the start or finish measuring point with points in the model or in the real environment.

Current built-in tools in the VisualLive HoloLive and Trimble Connect platforms continue to improve and new tools and functionalities are being added. The research team plans to carry out a 2nd phase of the research to test the technology and the new features on several new case studies and define a workflow to manage the as-built BIM turnover quality. Facility users will be invited to participate in the testing to give input and feedback on the usability and effectiveness of the tools. User feedback will be captured using a more detailed and structured questionnaire.

Future research also aims at exploring the HoloLens's remote assistance/interactive collaboration functionality to test advantages of user collaboration from different remote locations to manage as-built turnover quality. The research will also investigate means for automation of discrepancy measurement and capture by the Hololens.

Conclusion

Delivering FM-Capable BIMs at project handover is very critical to operation and maintenance and allows facility owners to manage their buildings more efficiently and effectively. Models should be data-centric, have accurate and complete representation of building components and systems, systems-centric, and allows for bi-directional exchange of data and information with the facility data management system. Initial testing conducted by the Virginia Tech- Procon Consulting research team aimed at exploring the usability and effectiveness of Mixed Reality technologies to verify the quality of as-built BIMs and ensure that model data and graphics are correct and complete (first two requirements for an FM-capable BIM).

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