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INVESTIGATING MIXED REALITY APPLICATIONS IN BUILDING INSPECTION AND MAINTENANCE

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Abstract: Facilities Management (FM) industry is frequently exploring new technologies with the potential to increase efficiency of inspection and maintenance processes of buildings. Mixed Reality (MR), which allows blending of real environment with virtual objects, is one technology that has such potential. The aim of this study is to develop an MR assisted system that can be used to enhance the process of inspection and maintenance of buildings. Three case scenarios were developed as a "proof of concept" to demonstrate the effectiveness of MR technology for inspection and predictive maintenance as compared to the systems in place. A 3-story academic building was used for testing. A mixed-methods research design consisting of a questionnaire survey and semi-structured interviews was adopted to collect the users experience data. The preliminary results showed that the MR technology has a potential to overcome limitations of the legacy FM systems. Nearly, two-third of the surveyed participants found MR system to be very effective in educating and training facility inspectors and technicians about routine inspection and maintenance tasks. However, several technical limitations were also identified such as MR model drifting, information access lags, and abrupt crashing of the system. Though limited in scope, this research study built foundations for carrying out a more detailed investigation on the effectiveness of MR technology for the FM industry. It is hoped that the reported results would be helpful for FM researchers and practitioners who are interested to explore advanced visualization technologies for improving efficacy and efficiency of inspection and maintenance processes.

Keywords: Facility management, Building inspection, Maintenance, Mixed reality, HoloLens

1 BACKGROUND AND RATIONALE

Facilities Management (FM) is an integrated approach for an organization to operate, maintain, improve, and adapt its buildings and infrastructures in a way such that the primary objectives of the organization, occupants, owners and facility managers are supported (Abdullah et al. 2013). FM comprises various areas, but it is Facility Maintenance Management (FMM) that constitutes most (65%~85%) of the total costs incurred by FM activities. Facility maintenance activities can be supported by Computerized Maintenance Management Systems (CMMSs) and Facility Management Systems (FMSs) as fundamental information sources, providing FM staff (facility managers and maintenance workers) with a wealth of support-related information as well as assisting management in decision making. Currently, many CMMSs and FMSs, such as ARCHIBUS™, EcoDomus™, Maximo™, and FM:Systems™ are available in the market. These systems can be used to manage the building inspection and maintenance processes and to provide an organized information management platform. However, options for automatic information capture and data analysis are still limited in CMMSs and FMSs (Chen et al. 2018).

The current practice of using FM systems for Operation and Maintenance (O&M) has two major limitations. First, the data input is mostly carried out manually, which is time-consuming, error-prone, and costly. Many check items must be inspected for numerous target objects according to the building standards, so there is a great risk that some of them may easily be missed out by the inspectors (Chen et al. 2018). Particularly, a huge amount of facility information is generated in the design and construction stages and such information may not be automatically imported into the current FM systems for further usage. Second, project documents are mainly stored as viewable PDF documents or 2D CAD drawings. Hence, the current O&M practices fail to provide FM staff with easy and prompt access to accurate facility data, thereby hindering effective and efficient O&M (Lin et al. 2017). Specifically, most of the existing FM systems do not provide digital visualization of workflows (Hu et. al. 2018).

Mixed Reality (MR), as defined by Paul Milgram in 1994, is the merger of real and virtual worlds (Milgram et. al. 1994). It essentially allows for digital objects to exist and interact with real objects in real time. Recent advancements in wearable visualization systems such as Microsoft HoloLens® have simplified MR hardware to the point where almost anyone can take advantage; no specialized knowledge is necessary to perform most tasks (Blackmon and Azhar 2018).

In relation to the problems, this research study develops and deploys a Mixed Reality (MR) system to enhance the users' cognitive and decision-making abilities through 3D immersive visualizations. Such a system may provide the following benefits: (1) Generation of an effective data collection and management portal so that the inspector and relevant individuals can quickly retrieve necessary information from the system to investigate certain areas of inspection and maintenance of the intended building; (2) It may reduce current labour-intensive methods by digitalizing the paper-based approaches; and (3) It creates a safer inspection environment using a hands-free head-mounted immersive display so that the inspector can maintain a real-world view of the inspection.

The aim of this study is to develop an MR system that can be used to enhance the process of inspection and maintenance of building facilities. The scope of the research is limited to academic buildings. The research objectives are as follows: (1) To adopt MR technology for on-site inspection and maintenance by deploying Microsoft HoloLens®; (2) To examine how MR technology can be effective in comparison to the current practises in FM; (3) To test how the proposed MR system can assist FM division of an academic institute in their routine building inspection and maintenance work; and (4) To investigate if the proposed system can be helpful in managing the FM database, improving client satisfaction, and saving time and cost as compared to the legacy FM systems.

2 LITERATURE REVIEW

The operations and maintenance phase is the longest and most expensive period within the lifecycle of a building (Abdullah et al. 2013). During this period, the building operators need to perform regular onsite maintenance tasks to prevent functional failures of building equipment and systems. Improving current onsite maintenance procedures can significantly reduce the overall life-cycle budget, since it is estimated that more than 80% of the entire life-cycle costs are actually spent on facility management (Neges and Koch 2016). In this regard, the visualization systems such as Augmented/Mixed Reality (AR/MR), and BIM technologies are recently explored as a potential asset to the FM industry. In the following paragraphs, notable research efforts in these mentioned areas are highlighted.

Building Information Modeling (BIM) can provide digital FM data repository and serve as an information backbone for FM systems by providing 3D object-based parametric data (Ghosh et. al. 2015). Wetzel and Thabet (2015) proposed a BIM-based FM framework to support safe maintenance and repair practices. Though their framework is based on locational data from BIM to provide more sophisticated information analysis, it just deals with the safety issues in the maintenance phase. Shalabi and Turkan (2016) stressed on BIM-based FM data collection for corrective maintenance work. They developed a BIM-based data repository for improving visualization and interoperability capabilities. To provide a reliable FM service, it is indispensable for FM personnel and building owners to capture critical information in the O&M phase. This is because the FM information analysis makes it possible to carefully plan for preventive O&M work (Oti et. al. 2016). In this regard, the 3D FM-BIM systems have an advantage of storing and outputting the location data. The FM personnel and building owners can obtain effective information for planning and decision making based on the location data (Oti et. al. 2016).

On-site building inspection requires rigorous data acquisition from paper or digital drawings and/or databases. The process is cumbersome and requires a significant amount of time. A one potentially viable solution to this problem is leveraging easier access to such data through mobile AR systems. Such systems can accommodate simpler, faster, and more accurate inspection processes by allowing users instant access to better visualizations of the BIM for the location they inspect (Kopsida and Brilakis 2016). One of the main problems in the current AR systems is in having an accurate alignment of the BIM on the user's view. Prevalent AR systems either provide information regarding onsite activities (Wang et al. 2013) or assist a defect management system using fiducial markers (Kwon et al. 2014). , A markerless solution based on the Kinect Fusion™ is suggested, to solve this problem since the new mobile AR devices are equipped with depth sensors. This solution combines the registration of the camera pose provided by Kinect Fusion™ with the registration achieved using the Iterative Closest Point (ICP) algorithm on the 3D reconstruction generated by Kinect Fusion™. The ICP algorithm minimizes the difference between the 3D reconstruction of the real scene and the 3D as-planned BIM model. A similar study has shown that inspectors favour mobile-based AR systems for simpler and prompt inspections than in-place FM systems (Gheisari et al. 2014).

Chen et. al. (2019) proposed an AR-based Facilities Management and Maintenance framework (FMM) which uses BIM as the data source, AR as a visualization tool and Wi-Fi-fingerprinting for indoor localization. Multiple algorithms for location registration were developed to locate nearest Wi-Fi fingerprints. Regarding BIM, two plug-ins were developed using Revit API to extract correct room information. For augmented reality, Unity 3D® was used to develop an AR user interface (UI) for smartphones. With the integration of all three systems, the framework helped to achieve 65% reduction in time taken to complete the task as compared to traditional 2-D plans with a localization accuracy of 1m. Future directions suggests working on the localization accuracy and minimizing dependency on the environment because of the limited coverage of Wi-Fi signals throughout the facility. To overcome the location accuracy, Jurado et. al. (2021) developed a markerless application (GEUINF) for smart phones that captures real world's 3D data by depth sensing to determine user's position and orientation with a centimeter accuracy. The researchers overcame the problem of positioning computer-generated renderings onto the real world by capturing 3D planar surfaces of user's environment and comparing them with virtual 3D model of the facility. It is evident from this study that ubiquitous smartphones are reliable devices for MR experiences in facilities operation and maintenance (Jurado et. al. 2021).

AR/MR integration with Heritage BIM (HBIM) is a novel application for preventive maintenance of historical buildings (Fonnet et. al. 2017). This study suggested the architecture of an innovative MR based maintenance system for the inspectors to identify and communicate the potential problems to the owners, well ahead of time. Authors employed Microsoft HoloLens® as a MR tool for the field application. Instead of using marker-based or marker-less approach for positioning purpose, the researchers used the spatial mapping technique to capture the surroundings and effectively placing the virtual model onto the real world.

Another novel application of AR/MR is conducted by Diao and Shih (2019) where they developed a BIM-based AR Maintenance System (BARMS) for cooling towers and plumbing. Markerless augmentation in changing light intensities (outdoor/indoor), safety route display, and 3D animated guide are some of the prominent features of this system. The application developed in Visual Studio® took input from 3D BIM model of piping facilities developed in Revit® and AR scenes in Unity 3D®. The result indicated high usability. However, even though the system used visual tracking, still it encountered some drifting problems which are to be addressed in future research.

Although this short review of the published literature shows significant efforts in developing and testing AR/MR technologies for inspection, operation and maintenance, most of the developed AR/MR systems are lab prototypes and not fully tested in the actual environment. The main motivation for this research is to develop a scalable MR system for routine building inspection and maintenance tasks, test it in the real environment via FM personnel, and get their professional feedback for improvement and further development.

3 RESEARCH DESIGN AND METHODOLOGY

Three case scenarios were developed as a "proof of concept" to demonstrate the effectiveness of MR technology for inspection and predictive maintenance as compared to the systems already in place. A 3-story academic building was used for deployment and testing. A mixed-methods research design consisting of a questionnaire survey and semi-structured interviews was adopted to collect the user experience data from a selected group of facility technicians, inspectors, and managers who work for Facilities Management (FM) division of Auburn University. The three case scenarios are explained in the following paragraphs.

The first case scenario is relevant to inspection and maintenance of "Hot Water system" and used to demonstrate standard operating procedures in an event where the hot water system fails to work. The workflow platform in the HoloLens® was built with supporting failure and repair imagery. A plumbing model pops up as soon as the inspector wears the HoloLens®. A checklist is created against the failure and repair imageries to guide the inspector about steps involved in inspection and repair.

The second case scenario is related to fixing the "Ceiling Light Fixtures" and consists of two modules; Module 1 guides the user about a step-by-step process of replacing the light lamp, while Module 2 steers the user to the procedures in an event where the ballast needs to be fixed. For each step or set of actions, there is an associated imagery guiding the user about the inspection and repair steps involved.

The third scenario is relevant to the inspection and operation of "Fire Sprinkler Systems". In this case, Microsoft Azure® repository, Windows Mixed Reality platform® and Unity 3D® are used for MR system development. A checklist with appropriate instructions is created in Unity 3D® to guide the user through the inspection and maintenance process step-by-step. 2D images and short videos are used for each step to be taken as a reference to execute that step.

Figures 1-3 shows the workflow and images of the developed MR system for "Hot Water System" inspection and repair. Due to limited space, the workflows and images of the other two case scenarios are not shown.

The MR system was tested by 12 professionals (facility technicians, inspectors, and managers) of a FM division of Auburn University. A standardized procedure was followed for testing, which included: (1) Subject(s) were read the exercise instructions aloud; (2) Subject(s) were familiarized with the HoloLens®; (3) Subject(s) were asked if they had any questions before testing; and (4) Subject(s) were visually observed. A post exercise questionnaire and semi-structured interviews were used to collect the necessary feedback data. Both questionnaire and interview questions were originally developed by the researchers.

A questionnaire consisting of 7 questions was designed to gather data for three assessments: (1) The Mixed Reality scenarios' effectiveness, (2) the HoloLens limitations, (3) and the HoloLens® overall potential for the FM industry. The purpose of Questions 1 and 2 was to assess the participants' opinions on the effectiveness of the MR system and HoloLens®. Questions 3 and 4 were designed to identify any system limitations and gauge learning curve associated with the HoloLens® use. Question 5 collected assessment data as to whether the HoloLens® could benefit the FM industry. Questions 6 and 7 were open-ended questions at the end of the survey, written to assess the case exercises effectiveness and collect any additional feedback.

The semi-structured interviews consist of the following questions:

1. Can a MR based system be effectively implemented in inspection, operation and maintenance of the building facility?

2. Were there any significant differences recorded in the quality of inspection, operation and maintenance while deploying the MR-based system instead of using legacy FM system?

3. What are some of the technological and design limitations, the MR system needs to overcome in order to see its widespread adoption in the FM industry?

4. Are there any time and cost benefits of introducing MR-based system in facilities operation and maintenance?

The semi-structured interviews were conducted in small groups to facilitate discussion and get answers to any follow-up questions. Collected data was analysed using appropriate data analysis methods and major findings are reported in the next section.

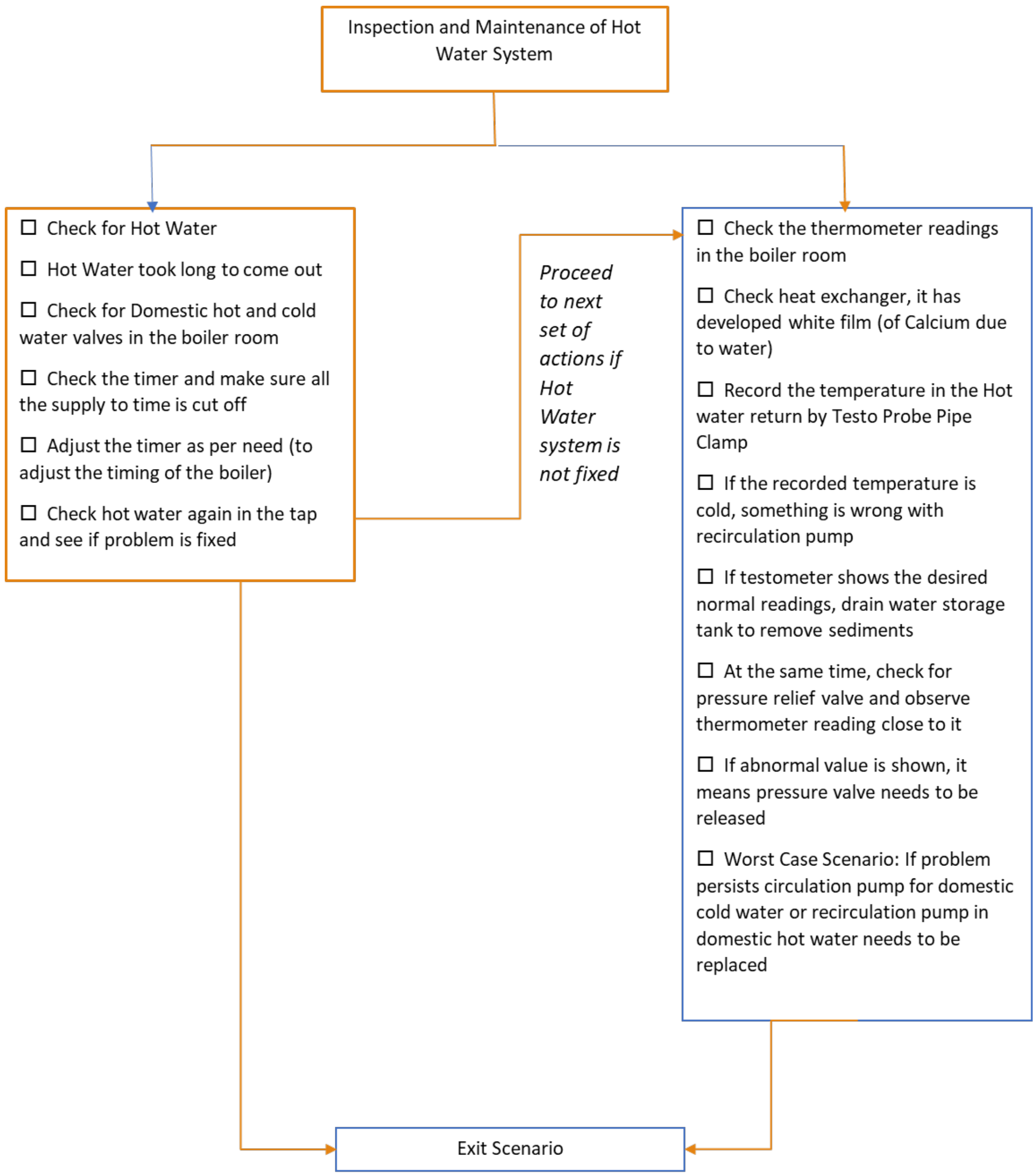

Figure 1: Flowchart showing the workflow for scenario 1 - inspection and maintenance of hot water system

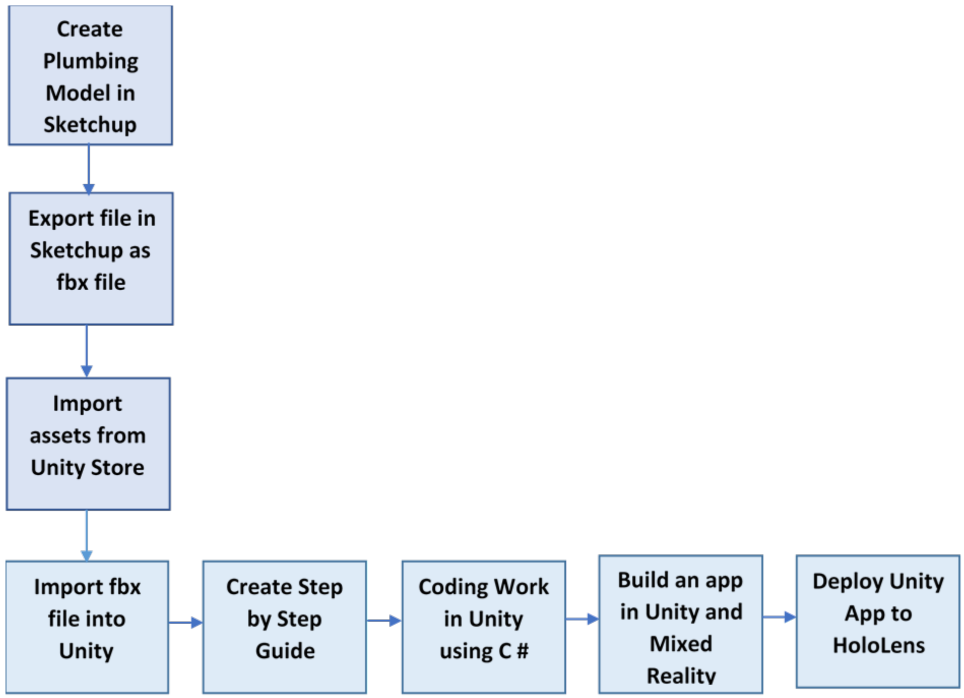

Figure 2: Flowchart showing the major steps for building the MR system for “Hot Water System”

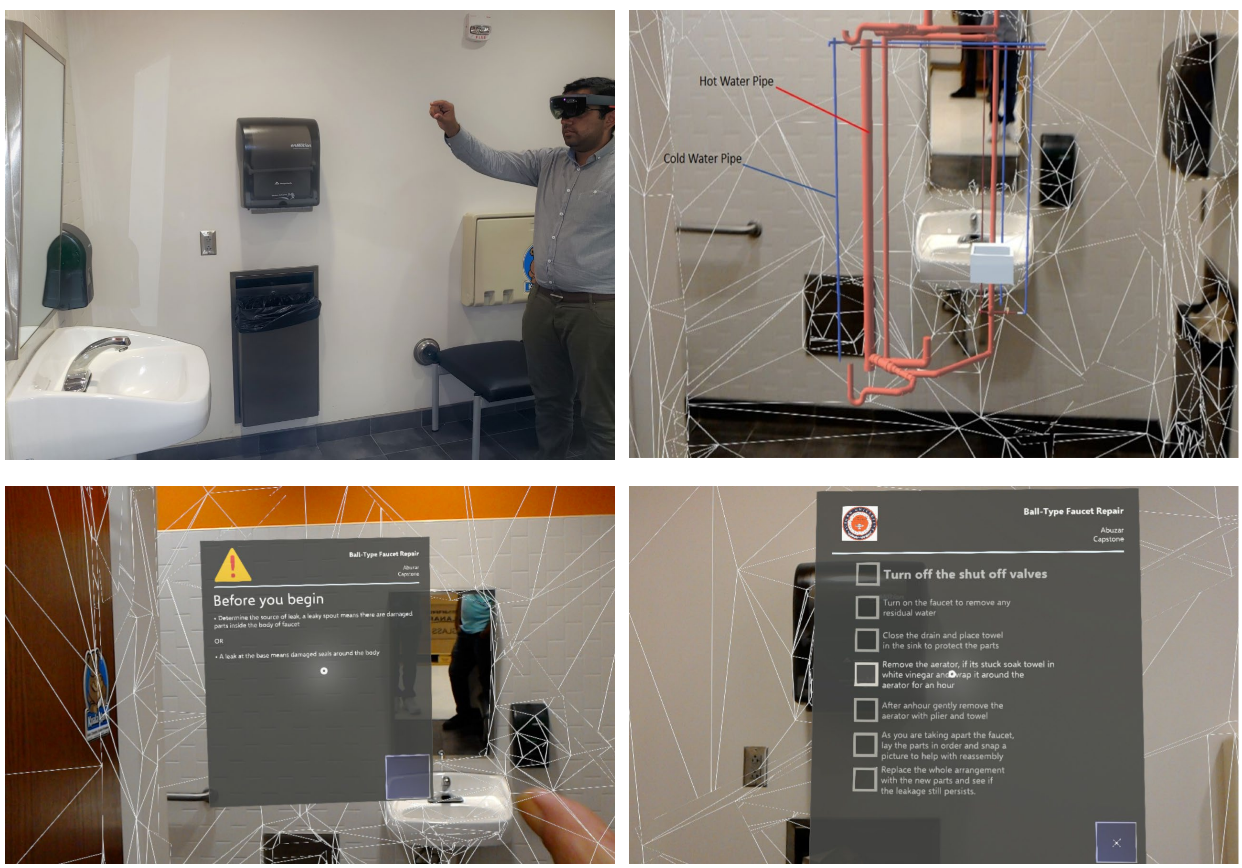

Figure 3: Images of the developed MR system for hot water system inspection and maintenance

4 MAJOR FINDINGS AND DISCUSSION

The questionnaire results are summarized as follows:

- *Easy Identification of Methods and Steps for Inspection and Repair:* Nearly two-third (8 or 66.7%) of participants rated the HoloLens® as "highly advantageous" for easy identification of methods and steps needed in equipment inspection and repair, while two (2 or 16.7%) participants thought it was of "little advantage" and two (2 or 16.7%) participants considered it of "no advantage at all".

- *Effectiveness of Interactive Environment:* Four (4 or 33.3%) participants thought the HoloLens® was "highly advantageous" concerning interactive environment (Utilities Model and Physical Environment), while half (6 or 50%) participants thought it was of "little advantage" and two (2 or 16.7%) participants thought it was of "no advantage at all".

- *Time Savings:* Half (6 or 50%) participants thought the HoloLens® was "highly advantageous" concerning time savings, while four (4 or 33.3%) participants thought it was of "little advantage" and two (2 or 16.7%) participants considered it of "no advantage at all".

- *Realistic Practical Experience Even Without Prior Knowledge of the System:* One-third (3 or 33.3%) participants thought the HoloLens® was "highly advantageous" concerning understanding realistic practical experience even without prior knowledge of the system, while remaining participants thought it of "little advantage" (3 or 33.3%) or "no advantage at all" (3 or 33.3%).

- *Case Scenarios:* Half (6 or 50%) of the participants reported that MR system was "extremely effective" in exposing them to building systems and the steps involved for inspection, while 17% of participants reported it to be "very effective" and remaining 33% reported it as "slightly effective". The weighted mean value maintained that overall participants felt that knowing building systems through MR and the steps involved for inspection were "very effective" as compared to the tradition FM systems.

- *Benefits of MR System:* Following benefits were reported by the participants: (1) Better ability to visualize the work, utility models and instructions; (2) Better interaction with the physical environment and more hands-free learning experience; (3) More data communication as actual 3D model of the equipment can be made accessible; and (4) Easy/ convenient equipment and steps identification to fix the problem.

- *Limitations:* (1) The projected/virtual checklist for the equipment sometimes fumbles with slight movement of the user; and (2) Using HoloLens® and getting familiarized with its system requires some training. It may at times get difficult to interact with it.

- *Suggestions for Improvement:* (1) More in-depth scenarios should be built to show the movement of levers with animations and labelling the system parts; (2) Field of view should be improved in the HoloLens®; and (3) More flexibility and data to pull up any 3D model and blueprints.

The major findings of the semi-structured interviews are as follows:

- *Can a Mixed Reality based system be effectively implemented in inspection, operation and maintenance of the Building Facility?* The participants validated and vouched for MR-based system implementation in the building facility's inspection, operation and maintenance. Most of them rated it as "very effective to extremely effective". All participants were able to complete the exercises using only the HoloLens®. The exercises were elaborate and simulated three scenarios very similar to how inspection, operation and maintenance is done in the FM division. This elaborateness of the simulation exercises further supports the case for use of MR system for facility management of the building.

- *Were there any significant differences recorded in the Quality of Inspection, Operation and Maintenance while deploying Mixed Reality based system?* The qualitative data gathered evidently supports that MR system proved to be far superior as compared to legacy FM systems when it comes to deploying them for inspection, operation, and maintenance of the facility. Nearly 83% of participants thought that the MR system was "extremely effective" in improving their long-term memory about identification of the steps involved in inspection and repair. About two-third of the participants thought that MR system was "extremely effective" in providing more understandable information than a traditional FM system.

- *What are some of the technological and design limitations that the Mixed Reality system needs to overcome in order to see widespread adoption in Facilities Management?* Following challenges were reported: (1) Spatial Registration: Spatial registration technology, also known as MR localization technology, can combine the virtual world and the real world through a proper relationship of the relative positions. It has been noted that placing the model and accurate identification of environment is a problem in MR based systems. Spatial registration has its limitations in either accuracy or practicality. To promote the application of MR in different fields of the FM, more advanced localization methods that can provide higher accuracy and can be easily accessed are needed. In fact, the emerging fifth-generation mobile networks (5G) technology has the potential to fill many of these gaps. The localization accuracy based on 5G can reach the centimeter level, given the high efficiency of the communication and high density of the base stations. No significant attenuation for 5G signals occurs in indoor environments, indicating the applicability of 5G to indoor localization; (2) Application Reliability: While the exercise is being conducted, the MR application and the HoloLens® turning off was reported by three participants. This affected the exercise time and also introduced bias in the participants that MR based systems are unreliable when it comes to handling complex processes. As the HoloLens® is relatively new, and developers are still getting used to developing MR applications, this limitation is not surprising. In this study, the first-generation HoloLens® was used. The second-generation HoloLens® has more computing and graphics processing power and would act better in complex situations.

- *Are there any time and cost benefits of introducing Mixed Reality based systems in Facilities Operation and Maintenance?* The participants reported moderate time savings however they were not able to provide any feedback about the cost. In fact, some of them raised concerns about possibly high costs due to increased training needs as well as managing data using paid cloud services.

5 CONCLUSIONS AND FURTHER RESEARCH

This research demonstrates that Mixed Reality (MR) based systems can successfully be used for inspection, operation and maintenance of the buildings. The research findings validated the use of Microsoft HoloLens® as a capable tool for guiding systematic systems' inspection, repair, and preventive maintenance. Specific improvements in the design and technology of HoloLens® are needed for its full-scale deployment in the FM industry.

The most immediate need for improvement is spatial registration technology, as successful maintenance and inspection would require the inspector to see the model overlaid exactly over the equipment. The information exactly overlaid on top of the equipment by using MR markers can give user more clear and crucial information about the equipment. Other shortcomings the HoloLens® must overcome before its widespread adoption is more stable view of the models, data and space as well as dedicated cloud services and 5G technology to share the data for multi-user collaboration. More so than anything, this study can serve as a proof of concept and foundation for further research in the area of MR use in FM.

If future research contemplates expanding this methodology, it should first address the following limitations: (1) Increasing the number and diversity of participants; (2) Labelling the assembly pieces non-sequentially; (3) Multi-user collaboration and remote collaboration to improve the process of inspection and maintenance; (4) Use of Mixed Reality markers to overlay information on top of equipment; (5) Developing more in-depth scenarios for HVAC, Plumbing and lighting systems inspection and maintenance.

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