Remote Collaborative BIM-based Mixed Reality Approach for Supporting Facilities Management Field Tasks

Khaled Nashba El Ammari

A Thesis
In the Department
of
Building, Civil, and Environmental Engineering

Presented in Partial Fulfillment of the Requirements
For the Degree of
Doctor of Philosophy (Building Engineering) at
Concordia University
Montreal, Quebec, Canada

November 2018

CONCORDIA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

This is to certify that the thesis prepared

By: Khaled Nashba El Ammari

Entitled: Remote Collaborative BIM-based Mixed Reality Approach for Supporting Facilities Management Field Tasks

and submitted in partial fulfillment of the requirements for the degree of

Doctor Of Philosophy (Building Engineering)

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

____ Chair
Dr. Zhibin Ye

____ External Examiner
Dr. Jeffrey Hudson Rankin

____ External to Program
Dr. Leila Kosseim

____ Examiner
Dr. Fuzhan Nasiri

____ Examiner
Dr. Ashutosh Bagchi

____ Thesis Supervisor
Dr. Amin Hammad

Approved by ____
Dr. Fariborz Haghighat, Graduate Program Director

January 11, 2019 ____
Dr. Amir Asif, Dean
Gina Cody School of Engineering and Computer Science

ABSTRACT

Remote Collaborative BIM-based Mixed Reality Approach for Supporting Facilities Management Field Tasks

Khaled Nashba El Ammari, Ph.D.
Concordia University, 2018

Facilities Management (FM) day-to-day tasks require suitable methods to facilitate work orders and improve performance by better collaboration between the office and the field. Building Information Modeling (BIM) provides opportunities to support collaboration and to improve the efficiency of Computerized Maintenance Management Systems (CMMSs) by sharing building information between different applications/users throughout the lifecycle of the facility. However, manual retrieval of building element information can be challenging and time consuming for field workers during FM operations. Mixed Reality (MR) is a visualization technique that can be used to improve the visual perception of the facility by superimposing 3D virtual objects and textual information on top of the view of real-world building objects. The objectives of this research are: (1) investigating an automated method to capture and record task-related data (e.g., defects) with respect to a georeferenced BIM model and share them directly with the remote office based on the field worker point of view in mobile situations; (2) investigating the potential of using MR, BIM, and sensory data for FM tasks to provide improved visualization and perception that satisfy the needs of the facility manager at the office and the field workers with less visual and mental disturbance; and (3) developing an effective method for interactive visual collaboration to improve FM field tasks. This research discusses the development of a collaborative BIM-based MR approach to support facilities field tasks. The research framework integrates multisource facilities information, BIM models, and hybrid tracking in an MR-based setting to retrieve information based on time (e.g., inspection schedule) and the location of the field worker, visualize inspection and maintenance operations, and support remote collaboration and visual communication between the field worker and the manager at the office. The field worker uses an Augmented Reality (AR) application installed on his/her tablet. The manager at the office uses an Immersive Augmented Virtuality (IAV) application installed on a desktop computer. Based on the field worker location, as well as the

inspection or maintenance schedule, the field worker is assigned work orders and instructions from the office. Other sensory data (e.g., infrared thermography) can provide additional layers of information by augmenting the actual view of the field worker and supporting him/her in making effective decisions about existing and potential problems while communicating with the office in an Interactive Virtual Collaboration (IVC) mode.

The contributions of this research are (1) developing a MR framework for facilities management which has a field AR module and an office IAV module. These modules can be used independently or combined using remote IVC, (2) developing visualization methods for MR including the virtual hatch and multilayer views to enhance visual depth and context perception, (3) developing methods for AR and IAV modeling including BIM-based data integration and customization suitable for each MR method, and (4) enhancing indoor tracking for AR FM systems by developing a hybrid tracking method. To investigate the applicability of the research method, a prototype system called *Collaborative BIM-based Markerless Mixed Reality Facility Management System (CBIM3R-FMS)* is developed and tested in a case study. The usability testing and validation show that the proposed methods have high potential to improve FM field tasks.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to my supervisor Dr. Amin Hammad for the continuous support of my Ph.D. study and related research, for his patience, motivation, and immense knowledge. His guidance helped me at all stages of research and writing of this thesis. I could not have imagined having a better supervisor for my Ph.D. study.

I would, also, like to thank the member of my committee, Dr. Jeffrey Rankin, Dr. Leila Kosseim, Dr. Ashutosh Bagchi, and Dr. Fuzhan Nasiri for their valuable inputs and precious time.

Furthermore, I would like to thank the rest of my research lab colleagues, especially Dr. Faridaddin Vahdatikhaki, for their insightful comments and encouragement and making the lab a great research environment. I would like also to thank Nassim Masoudifar for preparing the 3D visualization of the work order records. A special thank goes to the FM Department at Concordia University for providing FM data including 10-year work orders' records.

Last but not least, a special thanks to my family. Words cannot express how grateful I am to my mother and father for all of the sacrifices they have made for me. Your prayers for me were what sustained me so far. Most importantly, I would like to express my appreciation to my beloved wife who spent hard years with me and was always my support in the moments when there was no one else to comfort me.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	Description
3D	Three-dimensional
4D	Four-dimensional
ACMS	Advanced Computer based Management System
AEC/FM	Architecture, Engineering, Construction and Facility Management
ANOVA	Analysis of Variance
API	Application Programming Interface
AR	Augmented Reality
AV	Augmented Virtuality
BIFM	British Institute of Facilities Management
BIM	Building Information Modeling
CAD	Computer-Aided Design
CAFM	Computer Aided Facilities Management
CBIM3R-FMS	Collaborative BIM-based Markerless Mixed Reality Facility Management System
CG	Computer Graphic
CGI	Computer Generated Image
CMMS	Computerized Maintenance Management System
COBie	Construction-Operations Building Information Exchange
CV	Computer Vision
DOE	Design of Experiment
EAM	Enterprise Asset Management
FM	Facilities Management
FMS	Facilities Management System
FOV	Field Of View
GIS	Geographic Information Systems
GPS	Global Positioning System
HCI	Human-Computer Interaction
HMD	Head-Mounted Display
HTML	HyperText Markup Language
HVAC	Heating, Ventilation and Air Conditioning
IAI	International Alliance of Interoperability
IDM	Information Delivery Manual

IFC	Industry Foundation Classes
IFMA	International Facilities Management Association
IMU	Inertial Measurement Unit
IVC	Interactive Visual Collaboration
LBC	Location-Based Computing
LOD	Level Of Detail
MM	Maintenance and Management
MR	Mixed Reality
MVD	Model View Definition
NBIMS	National Building Information Model Standard
NIBS	National Institute of Building Sciences
NIST	National Institute of Standards and Technology
OGC	Open Geospatial Consortium
OR	Oculus Rift
RF	Radio Frequency
RFID	Radio Frequency Identification
RPC	Remote Procedure Call
RTLS	Real-Time Location System
UI	User Interface
UWB	Ultra-Wideband
UX	User Experience
VE	Virtual Environment
VR	Virtual Reality
VTM	Vuforia Target Manager
W3C	World Wide Web Consortium
WLAN	Wireless Local Area Network
XML	eXtensible Markup Language
XRefs	External Reference

CHAPTER 1 INTRODUCTION

1.1 GENERAL BACKGROUND

The scope of Facilities Management (FM) is fragmented and depends on the size of the facility and its management approach. The complexity of the management approach affects the collaboration between the stakeholders, which include the facilities managers, inspectors, maintenance workers, suppliers, facility owners, and facility users. There is a need for better coordination to overcome the barriers to information sharing among the stakeholders, which lead to decreased efficiency and productivity (Becerik-Gerber et al. 2011). Furthermore, Computerized Maintenance Management Systems (CMMSs) use knowledge-intensive processes, which are becoming increasingly challenging due to the uncertainty issues implicated in the collected data related to the facility condition evaluation. Consequently, facility inspection evaluation results may vary depending on the accuracy of inspection data input and the inspectors' expertise. In addition, constructing the database is essential and considered as a core part of the CMMSs. This database is built up of facility information (i.e., geometric and non-geometric information) and other information obtained by the regular facility inspection or collected directly by sensors (e.g., smoke detectors). The CMMSs require the inspector to find and accurately record defects during an inspection task.

Building Information Modeling (BIM) is a promising technology that can be used to enhance interoperability between different software tools by sharing the facilities information throughout the lifecycle (Underwood and Isikdag 2011). The integration of CMMS and BIM data can be used for visualization, which can facilitate heuristic problem-solving.

Furthermore, the collaboration aspect of any CMMSs is critical to improve the efficiency and productivity levels (Syafar et al. 2015). In practice, there are several commercial web-based CMMSs, such as NetFacilities (Netfacilities 2018) and Maintenance Connection (MaintenanceConnection 2017), that link people, places, and other resources to collaborate in real-time with all stakeholders. However, these systems lack Interactive Visual Collaboration (IVC), which can be partially supported by the tools that use BIM. There are several methods that can be used to support collaboration in executing FM processes including video recording, location tracking of FM resources, and Mixed Reality (MR).

1.2 PROBLEM STATEMENT

Based on the conducted literature review discussed in Chapter 2, several research issues in FM domain for supporting field tasks have been identified. These issues are limiting the FM field tasks, and they can be categorized as the following: (1) Data capturing and recording issues, (2) Visualization issues, and (3) Collaboration issues.

(1) Data capturing and recording issues

Information is the lifeblood of FM and an excessive amount of time is spent to locate and verify specific facility information (Gallaher et al. 2004). Furthermore, two surveys (Madritsch and May 2009, Williams et al. 2014) suggested that many facilities managers (45.95%) find it difficult to acquire the data for their systems, and that it can take a long time to populate the database. Furthermore, capturing location information in current practice using traditional or digital maps, pictures and drawings can lead to ambiguity and errors in interpreting the collected information (Sun et al. 2017). In addition, much valuable data associated with the design, construction, and operation of a facility is lost during its lifecycle (Gallaher et al. 2004). According to the U.S. National Institute of Standards and Technology (NIST), the lack of software interoperability in the Architecture, Engineering, Construction and Facility Management (AEC/FM) industry costs US$15.8 Billion annually (Williams et al. 2014). Although BIM has been utilized in CMMSs (e.g., Maximo-BIM360 viewer integration (IBM 2016), these systems lack the functions required to facilitate data collection, data entry, and data retrieval. In addition, navigation in complex 3D models is time-consuming (Syafar et al. 2015).

Furthermore, CMMSs use knowledge-intensive processes, which are becoming increasingly challenging due to the uncertainty issues implicated in the collected data related to the facility condition evaluation. Consequently, facility inspection evaluation results may vary depending on the accuracy of inspection data input and the inspectors' expertise. In addition, populating the databases is essential and considered as a core part of the CMMSs. These databases are built up of facility information (i.e., geometric and non-geometric information) and other information obtained by the regular facility inspection or collected directly by sensors (e.g., smoke detectors). The CMMSs require the inspector to accurately find and record defects during an inspection task. However, conventional CMMSs provide limited support for spatial data collection. Besides, locating a specific building element in a 2D or 3D model is time-consuming due to the complexity of the design, and this may distract inspectors from performing their tasks.

(2) Visualization issues

Unlike designers and contractors, FM operation personnel need for graphical data reduces over a building's lifetime (Teicholz 2013). Despite the visual benefits of BIM, the need for detailed graphical data decreases over a facility's lifetime, and FM is more concerned with building elements' informative attributes, equipment inventory, and how CMMSs can utilize this information effectively (Williams et al. 2014). However, keeping the spatial aspects of the BIM data is essential for facility field workers to perform inspection or maintenance tasks. Figure 1-1 shows what FM operator really need through the facility lifecycle. It shows that FM operators need BIM data and element attributes more than the graphical data. In addition, BIM in management practice showed the lack of managers and owners awareness and support, and lack of cooperation from other industry partners (Sun et al. 2017).

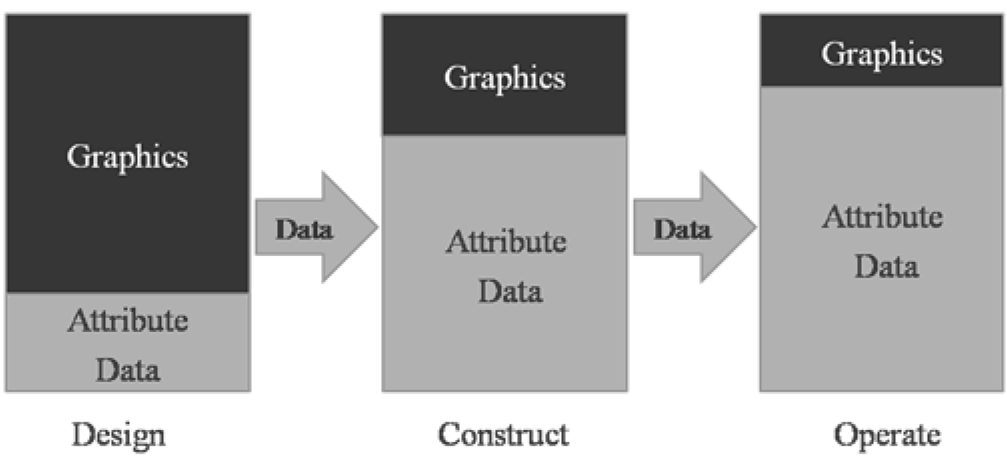


Figure 1-1 The need for graphical data reduces over a building's lifetime (Teicholz 2013)

Visualizing complex FM-related data, including geometric and non-geometric information, to the field worker may have negative impact of the task performance. For example, showing all unrelated previous and future inspection tasks may confuse the facility inspector about what to do and how to sequence and prioritize his tasks. On the other hand, showing timely and location-based necessary visual data (e.g., target HVAC duct for inspection) can help the inspector to focus on the inspection task in less time and be more efficient. Furthermore, task-related visual information can improve the safety of field workers. For example, installing pipes inside a wall requires drilling, which can be dangerous due to the wiring or other existing pipes installed inside the wall. Visualizing the existing wires and pipes and the safe location for drilling is critical to perform the task safely. That potential hazard can be avoided by showing all drywalls and concrete walls from BIM.

Other visualization issues related to the inspector perception of what is real and what is virtual are important for safety and for task perception. For example, introducing different rendering techniques (e.g., virtual hole and multi-layer of visual data) may assist the inspector to effectively diagnose the defect and better understand the workspace environment. Figure 1-2 shows examples of inspections and maintenance tasks where the accuracy of visualizing what is hidden is important.

(a) for plumbing (b) for electrical wiring (c) for HVAC ducts

Figure 1-2 Examples of maintenance tasks

FM has different requirements from other phases of the facility lifecycle. Visualization is one of these requirements, which can be improved using MR. However, MR-based CMMSs rely on FM-specific tracking, rendering and interaction technologies. For example, applying MR in the design phase requires a different tracking accuracy from what is required in the inspection and maintenance phase where the accurate location of defects is essential. Therefore, understanding and classifying the rendering, tracking and interaction requirements are important to support MR-based CMMSs.

(3) Collaboration issues

During complex facility operations, problem-solving still requires a team of experts to physically meet and interact with each other. The identification of the problem and the creation of a shared understanding are major challenges for efficiently solving a problem (Piirainen et al. 2012). FM operations require collaboration and support from FM experts for decision-making related to managerial or technical problems. The lack of collaborative support negatively affects the onsite workers' ability to sort out onsite problems (Sidawi and Alsudairi 2014).

According to Kestle (2009), misinterpretation and miscommunication of project results and lack of delegated authority to field workers often hinders progress. This miscommunication between stakeholders can lead to a number of avoidable errors, such as those caused by wrong facility element identification, wrong data entering/re-entering, wrong interpretation, and difficulties in supporting field tasks with expert knowledge when needed. Furthermore, the collaboration between the office manager and the field worker in real-time is not limited to data sharing. The two stakeholders need to collaborate in real time to perform one task (e.g., a scheduled inspection task for an HVAC ducts). However, this real-time collaboration has several requirements including tracking, visual communication and interaction methods to facilitate performing the inspection task and the collaborative decision-making.

1.3 RESEARCH OBJECTIVES

The objectives of this research are: (1) Investigating an automated method to capture and record task-related data (e.g., defects) with respect to a georeferenced BIM model and share them directly with the remote office based on the field worker point of view in mobile situations; (2) Investigating the potential of using MR, BIM, and sensory data for FM tasks to provide improved visualization and perception that satisfy the needs of the facility manager at the office and the field workers with less visual and mental disturbance; and (3) Developing an effective method for interactive visual collaboration to improve FM field tasks.

1.4 THESIS STRUCTURE

This research proposes a framework for remote collaborative BIM-based mixed reality approach for supporting FM field tasks. It consists of eight chapters:

Chapter 2 presents the literature review related to FM including challenges, CMMSs, and the use of BIM in AEC/FM, a comprehensive review of MR technology and its applications in AEC/FM industry and location tracking methods for MR applications.

Chapter 3 introduces the inspection processes re-engineering which is required for the proposed Collaborative BIM-based Markerless Mixed Reality Facility Management System (CBIM3R-FMS) framework. It discusses the proposed framework including data preprocessing, multisource large-scale modelling and the system architecture. The chapter also discusses the main functionalities and components of CBIM3R-FMS.

Chapter 4 discusses the methods for modeling and visualization for CBIM3R-FMS including the virtual hatch and the multilayer views; and the proposed tracking methods for the AR and IAV modules. The data preprocessing and database creation and connectivity is discussed.

Chapter 5 discusses the Interactive Visual Collaboration (IVC) method, its interactions sequence, interaction processes, and modalities of CBIM3R-FMS' gesture-based interactions.

Chapter 6 this chapter is dedicated to the implementation of the research framework and methods discussed in Chapters 3, 4 and 5. The implementation of CBIM3R-FMS and its two modules is discussed including hardware and software requirements, and the implementation of AR-IAV remote interaction and BIM data retrieval. In addition, a case study is presented in this chapter.

Chapter 7 the validation of the research method is presented in this chapter including the test participants, scenario, and statistical analysis of the usability testing. A comprehensive discussion is provided about the validation results of the IVC accuracy and effectiveness.

Chapter 8 has the research contributions, conclusions, limitations and the future work.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter reviews the three major research components including: (1) FM practices and emerging technologies in AEC/FM and their challenges, (2) BIM issues for AEC/FM, and (3) MR in AEC/FM. The current practice issues in the FM domain are discussed, and CMMSs solutions and systems are reviewed. Other issues such as interoperability are also discussed. FM and its related tools in terms of compatibility with BIM are also covered in this chapter. Furthermore, facilities' defect detection methods are also discussed. In the second part, a comprehensive review is introduced on the current status of BIM applications for AEC/FM, the potential challenges of using BIM, and BIM interoperability standards. Furthermore, in the last part of the literature review, a comprehensive review is undertaken on Mixed Reality (MR) technologies including Virtual Reality (VR) and Augmented Reality (AR), and their current applications in AEC/FM. In addition, more focused review is conducted on visualization and collaboration issues in MR-based AEC/FM applications. Location tracking in mobile MR-based applications is an important component. Therefore, location tracking methods for MR Applications including Real-Time Location Systems (RTLSs) and Computer Vision (CV)-based tracking are discussed.

MR can extend the perception capabilities of the user in the real world and improve the interaction with the augmented objects, providing information that the user cannot detect personally and directly (Izkara et al. 2007). The application of MR has been researched in different domains, such as in construction for supporting building inspection (Koch et al. 2012), for proactive construction defect management using BIM (Park et al. 2013), and for facilitating pipe assembly (Hou et al. 2013). Irizarry et al. (2013) proposed a method for accessing building information through a situation awareness approach. A review of AR research and applications in AEC/FM was conducted by Rankohi and Waugh (2013). However, there are still issues related to the taxonomy of visualization (when, what, and how to augment) and collaboration (e.g., levels and types of interaction, immersion, telepresence) that need more investigation. In addition, Gjøsæter (2012) presented a taxonomy of Handheld AR (HAR) applications.

During complex facility operations, problem-solving still requires a team of experts to physically meet and interact with each other (Lukosch 2015). The identification of the problem and the creation of a shared understanding are major challenges for efficiently solving a problem (Piirainen et al. 2012). The lack of field tasks' collaborative support negatively affects onsite workers' ability to sort out problems (Sidawi and Alsudairi 2014). Furthermore, the long physical distance between project participants is one of the primary causes of delays in decision making (Deng, Z. et al. 2001). As stated by Kestle (2009), misinterpretation and miscommunication of project results and lack of delegated authority to field workers often hinder progress. The miscommunication between stakeholders can lead to a number of avoidable errors, such as those caused by wrong facility element identification, wrong data entering/re-entering, wrong interpretation, and difficulties in supporting field tasks with expert knowledge when needed. Furthermore, the collaboration between the office and field workers is not limited to data sharing, as they need to collaborate in real time to perform inspection or maintenance tasks. Real-time collaboration using MR can help solving these issues by providing better visual communication and interaction.

2.2 FACILITIES MANAGEMENT

According to the British Institute of Facilities Management (BIFM) (BIFM 2016), FM is the integration of processes within an organization to maintain and develop the agreed services, which support and improve the effectiveness of its primary activities. FM acts as integrated management of all types of buildings from commercial, hotels and high-rise buildings to industrial and healthcare facilities. FM can also be defined as the management of hard and soft services. As an example of hard services, a building's HVAC system should be operating efficiently and safely. Whereas soft services in ensuring that the building is cleaned regularly. Nor et al. (2014) discussed the history and evolution of FM. The study shows that the impact of the emerging information technology has a major influence on how FM is changing. As shown in Figure 2-1, during the facility operation phase, the facility managers are responsible of keeping the function of the facility by integrating people, places, processes, and technologies such as BIM, Geographic Information System (GIS), Radio-frequency Identification (RFID), etc. (IFMA 2011).

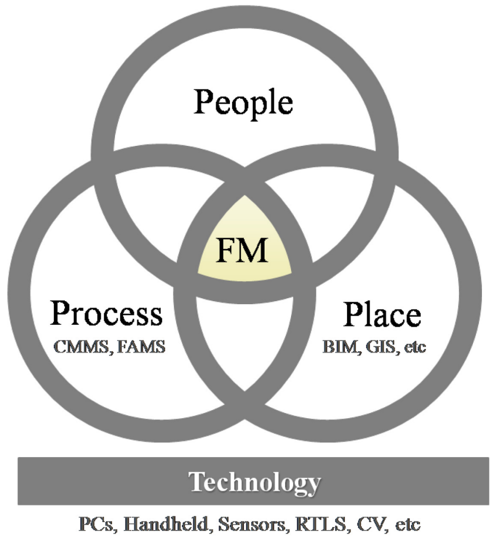


Figure 2-1 Facility management components (adopted from FDM 2001)

Gheisari and Irizarry (2016) conducted a survey of 80 participants and they identify the percentage of different types of information facility managers are using as shown in Figure 2-2. They also indicated that only 33% of facility managers use tablets and 17% use phones to perform their FM tasks.

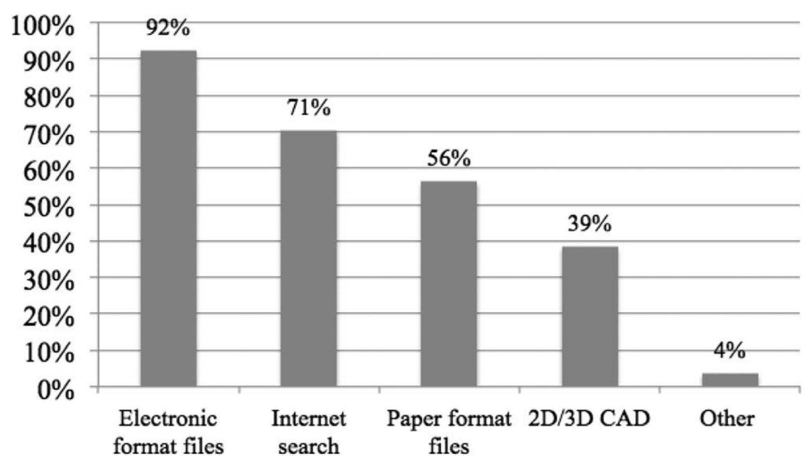


Figure 2-2 Information types used by facility managers (Gheisari and Irizarry 2016)

2.2.1 Facilities management challenges

FM is a complex and demanding industry because it involves different types of buildings with different functionalities and it involves a wide range of stakeholders with different points of interest. For example, the maintenance staff requires different information related to how to perform the maintenance tasks efficiently. On the other hand, facility managers are more concerned about operating the facilities with less service interruption at less cost. Furthermore, before performing maintenance tasks, facility managers need accurate information about defected building elements so that they can allocate the right skills and tools required to perform those tasks. For that reasons, sharing the related information between the office and field workers is very important. This information includes the defect type, severity, and location. At the planning stage, the facility managers plan the maintenance tasks based on many factors such as defect severity, the availability of the required skills, tools and budget. Field workers require additional information related to the maintenance workspace or nearby critical elements (e.g., electrical wiring). This kind of information helps the field workers to work efficiently and safely. Furthermore, the stakeholders may require direct collaboration and information exchange to prevent extra work and avoid any delays that may eventually affect the allocated budget for that specific task.

2.2.2 Computerized Maintenance Management Systems

A Computerized Maintenance Management System (CMMS) is software that helps maintenance teams keep a record of all assets, schedule, and track maintenance tasks and keep a historical record of the work they perform. In the FM industry, CMMSs may have different names such as Enterprise Asset Management (EAM) software, Facilities Management System (FMS), Maintenance Management Software, and Work Order Management Software (BIFM 2016). In most of these tools, facilities managers can select a piece of equipment or a building element with a defect, describe its problem and assign a specific technician to do the work. When the problem is fixed, the responsible field worker marks the work-order as "complete" and the manager gets notified that the work is done (Nor et al. 2014). These systems allow defects information to be tagged on the specific CAD 2D drawing. Bluebeam Revu is an iOS application that can be installed on an iPad where the user can access, navigate and annotate 2D drawings (Bluebeam 2017).

Selecting the most appropriate CMMS means finding a flexible application to easily adapt to the users' work environment. The main features to consider when choosing a flexible CMMS are: (1) report generation capabilities, (2) on-site labeling, (3) technical support, and (4) interoperability and system integration capabilities. Generally, CMMSs should be able to interface and integrate with other applications such as accounting, human resources, and building control systems. The interoperability feature enhances the productivity of both facilities managers and field workers and eventually saves time. In general, CMMSs can be evaluated based on their input-output capabilities as shown in Figure 2-3.

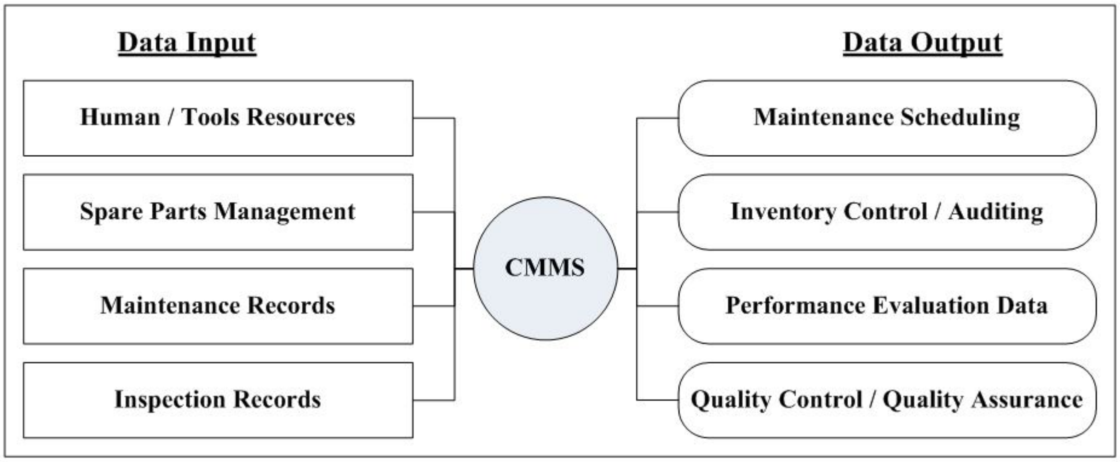


Figure 2-3 CMMS input-output diagram (Thomas and O'Hanlon 2011)

According to the U.S. Department of Defense (DOD), their facilities are accomplishing a huge number of work orders annually using their Defense Medical Logistics Standard Support (DMLSS). This manual process, as shown in Figure 2-4, costs almost 114,322 man-days at an estimated cost of US$113.4 million per year (Hagan 2015). They claim that enabling automation and process improvement in CMMS and Computer-Aided Facility Management (CAFM) can help in reducing the cost to 30 % and provide dramatic improvements in facility performance and customer service.

In addition, several FMSs are commercially available to satisfy the FM industry needs. Due to the fact that the implementation of BIM-based FMSs, which is discussed in Section 2.3.1, can be complex and expensive and may face resistance to adopt, many major BIM-based software providers, such as Autodesk, Graphisoft, and Bentley Systems, offer products along with consulting services for their clients.

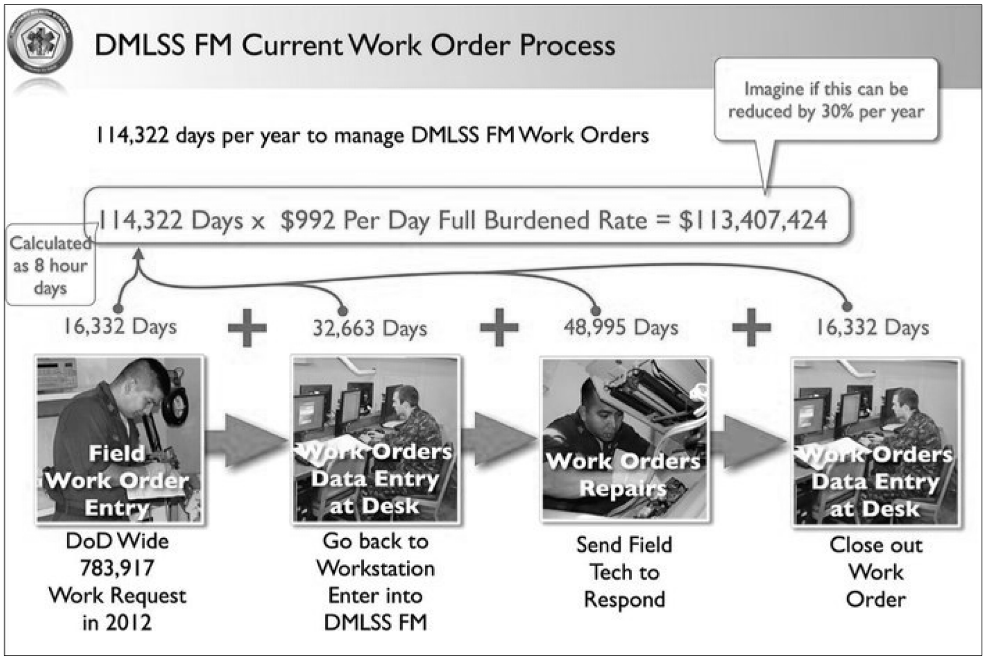


Figure 2-4 IFMA calculations of the current FM work order process (Hagan 2015)

Figure 2-5 shows an example of FMS (i.e., *FM:Systems*) integration with BIM. The system server side is connected to a database and to a BIM-based modeling tool (i.e., Autodesk Revit) and CAD-based drawings. The FM side is called *FM:Interact* and it includes real estate, space management, and maintenance interfaces. The system supports remote collaboration in terms of remotely sharing facility and maintenance related data (Schley 2012). However, such collaboration does not support location-based task performing where the field worker can update the system based on his task and share all information with the interested stakeholders. In addition, the system focuses on data sharing rather than task performing and experience sharing, which are more effective in making the right decisions.

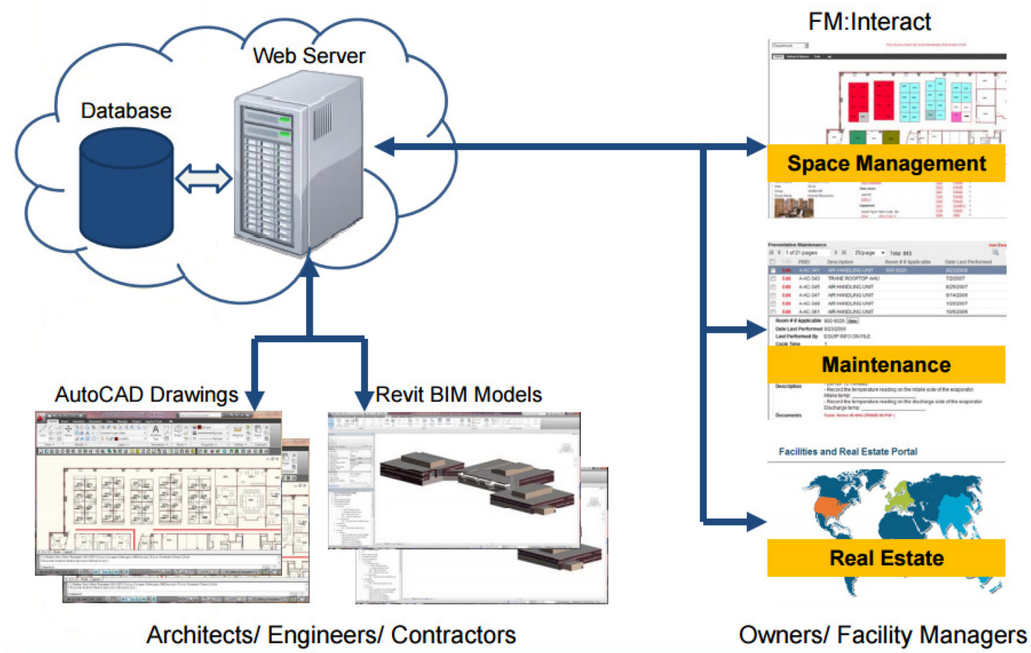


Figure 2-5 FM:Systems direct BIM integration (Schley 2012)

2.2.3 Defect inspection methods

Even though inspection sounds an easy task, there are many subtasks involved which are subject to mistakes and misinterpretation. In addition, manual data collection is time-consuming and error-prone processes. Furthermore, defects detecting is the initial step towards repairing the defected building elements. There are several inspection methods, which can be categorizes as traditional visual inspection or sensor-based inspection. In the traditional inspection method, the inspector is required to perform either visual inspection and should be physically present and in contact with the element to examine it. On the other hand, the sensor-based inspection method uses sensory data to analyze the condition of the element. CV-based technologies provide useful information to detect potential defects. For instance, thermal imaging provides inspectors with the heat signature profile for the inspected element. This profile helps diagnose the defected element and the potential causes of this defect (e.g., false ceiling corrosion caused by HVAC leakage).

Figure 2-6 shows an example of handheld thermal imaging device used in inspection. Morton (2013) indicates three benefits of thermal imaging in facilities inspection: (1) spotting electrical issues; (2) identifying thermal performance; and (3) detecting roofing and building envelope problems.

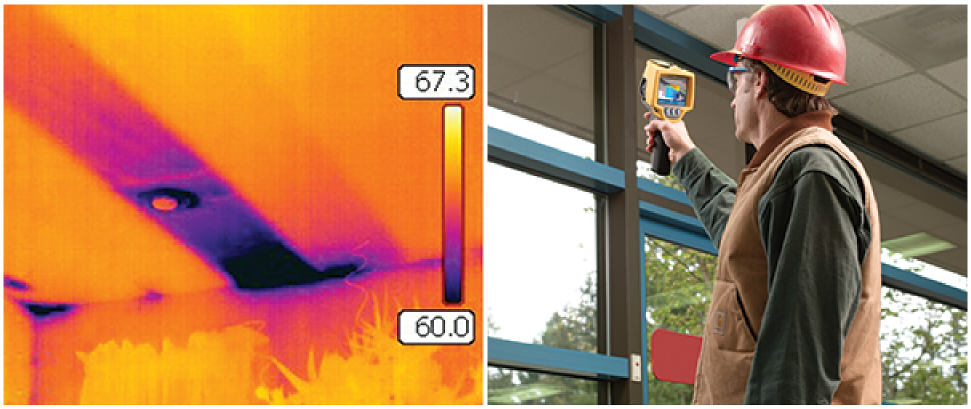


Figure 2-6 Thermal imaging handheld device used in building inspection (Morton 2013)

2.3 BUILDING INFORMATION MODELING

Many stakeholders, including facilities owners, facilities users, facilities managers, inspection and maintenance staff, and parts suppliers, require a common language of communication that allows them do their tasks effectively without interrupting other stakeholders or causing delays. BIM is a promising technology that helps all FM's stakeholders work together, which effectively increases efficiency. Figure 2-7(a) shows the document-centric approach, which has several challenges for information sharing, where Figure 2-7(b) shows the centric information approach. Sjogren and Sjogren and Kvarsvik (2007) listed the main issues with the document-centric approach. These issues can be communication errors and loss of project information within the same domain, or re-entering information on average seven times in different systems before the delivery of the facility to the owner.

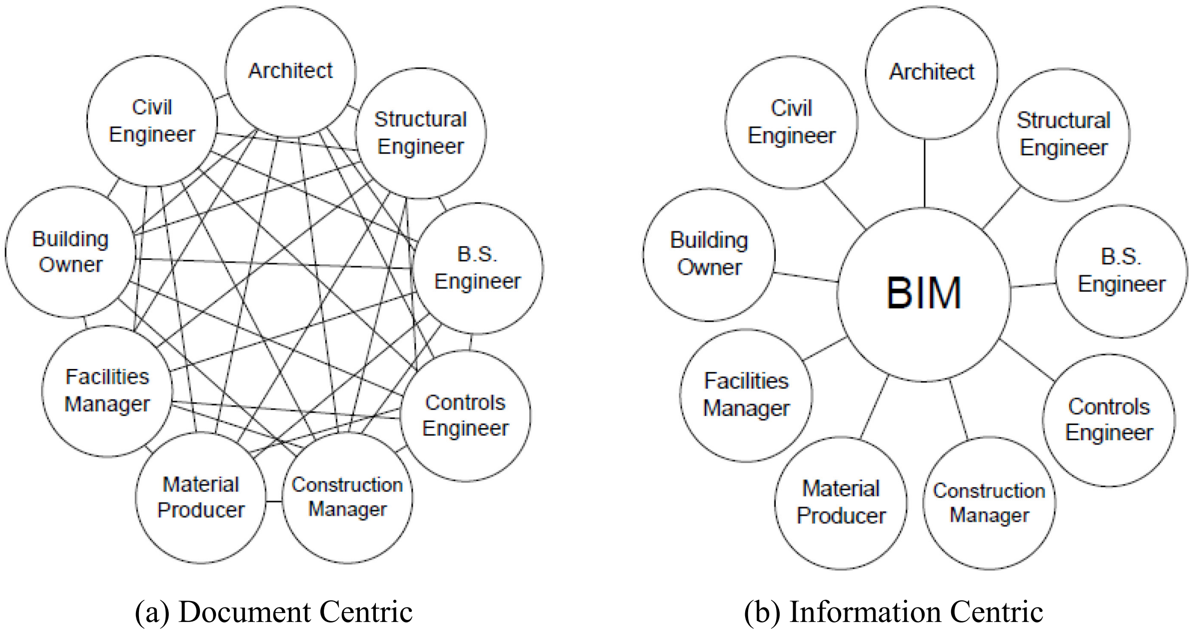


Figure 2-7 Document and information-centric approaches (Sjogren and Kvarsvik 2007)

In the centric information approach, all the stakeholders are able to communicate to each other through a common language by using BIM technology as a single repository for all the information. In addition, the parametric nature of BIM assists in design decision making, production of quality construction documents, prediction of building performance, cost estimating, and construction planning (Eastman et al. 2011). BIM can also be used in renovation or demolition work (Becerik-Gerber et al. 2011). Figure 2-8 shows that BIM can be used during the whole lifecycle of a facility from the design phase to the demolition.

Using FM-related information during the earlier phases can also increase the performance efficiency of the facilities. According to McGraw Hill Construction Smart Market Report (2012), using BIM by designers and contractors is as high as 70 and 74%, respectively, with about 67% design engineers using BIM. However, fewer FM teams today are actively using BIM. FM industry leaders are still defining how BIM can be used by facilities managers for new construction, major renovations and for existing buildings (Teicholz 2013).

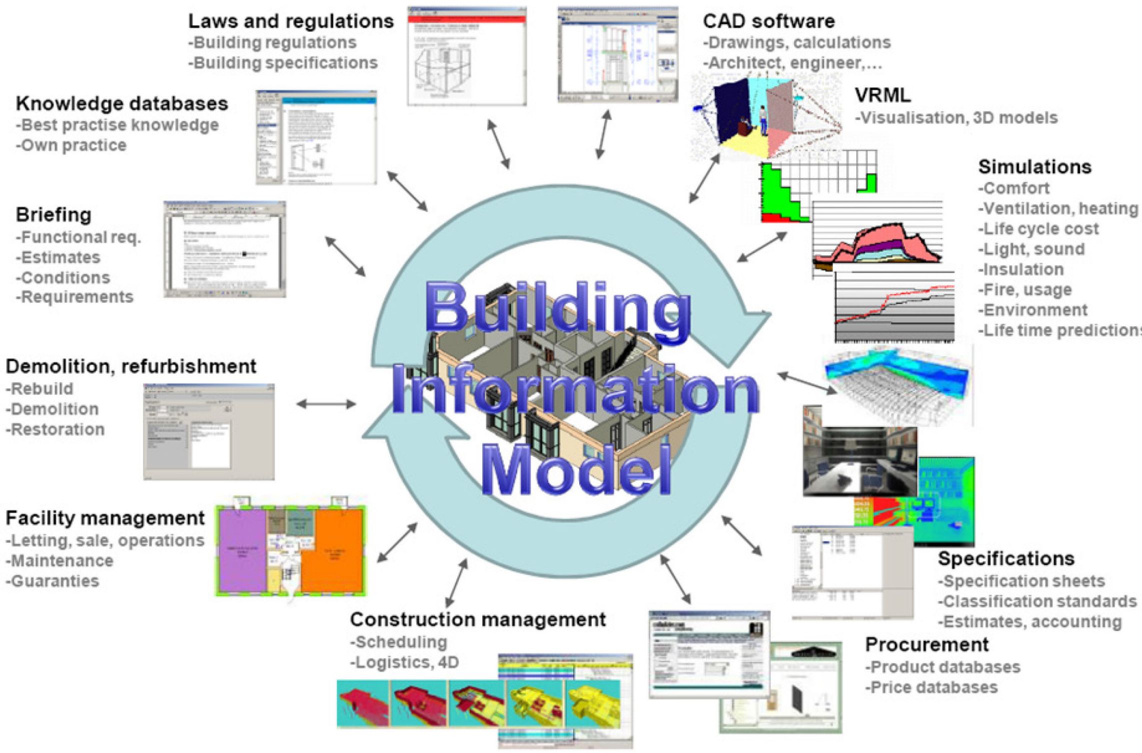


Figure 2-8 Lifecycle information view (NIBS 2018)

2.3.1 Building Information Modeling in AEC/FM

As a rich interoperability standard data format, the BIM model provides new opportunities to improve the efficiency of FM by sharing building information between different systems throughout the lifecycle. The 3D geometric data of BIM can be directly linked to CMMSs where the inspection related data are added to the system database. Furthermore, the integration between CMMSs and BIM can be used for visualization that eventually facilitates heuristic problem solving and provides an opportunity for visual analytics (Motamedi et al. 2014). To identify the role of BIM, Becerik-Gerber (2011) conducted a study based on interviews with FM personnel. Their research indicated that using BIM in AEC/FM can decrease the chances of errors and increase efficiency. Industry Foundation Classes (IFC) allows exchange of information among various tools in the BIM environment, and it is considered as the most widely used interoperability format in the AEC/FM industry (Nizam and Zhang 2017). IFC Extensible Markup Language (ifcXML) is a popular format to transfer BIM data to CMMSs and it provides use cases for specific IFC model definitions (Chen and Clarke 2017). CityGML is a rich information model with several Levels of

Details (LODs), which allows visualization and spatial analysis of 3D virtual city models in different application domains, such as simulations, urban data retrieval, and facilities management (Gröger and Plümer 2012).

In another research study conducted by Gheisari and Irizarry (2016), the survey respondents were asked to rate the applicability of BIM for FM purposes in 11 categories on a scale of very low (1) to very high (5). The survey results show that respondents rated locating building components (3.37) and 3D visualization (3.31) as the highest categories.

The challenges of using BIM in a project can be summarized as the following: (1) Level of awareness of the project owners and their understanding of BIM-based collaboration for FM; (2) Interoperability and standardization issues; (3) Identifying and deciding what LOD is required to achieve the project objectives; and (4) Visualization representation of different phases of project's lifecycle is not fully mature in existing BIM. For example, more information needs to be added to the existing BIM, such as element defects including the associated attributes (e.g., defect's type, location, severity). As shown in Figure 2-9, Sun et al., (2017) have categorized the main factors limiting BIM applications in AEC/FM industry.

According to their research, there are several factors including the cost and time needed to train staff, and the resistance to adopting new methods. In addition, the lack of collaboration from other industries has a great impact on limiting the implementation of BIM. Moreover, building a BIM model can be expensive since it requires gathering data from different sources and integrating in one data model that different users can share.

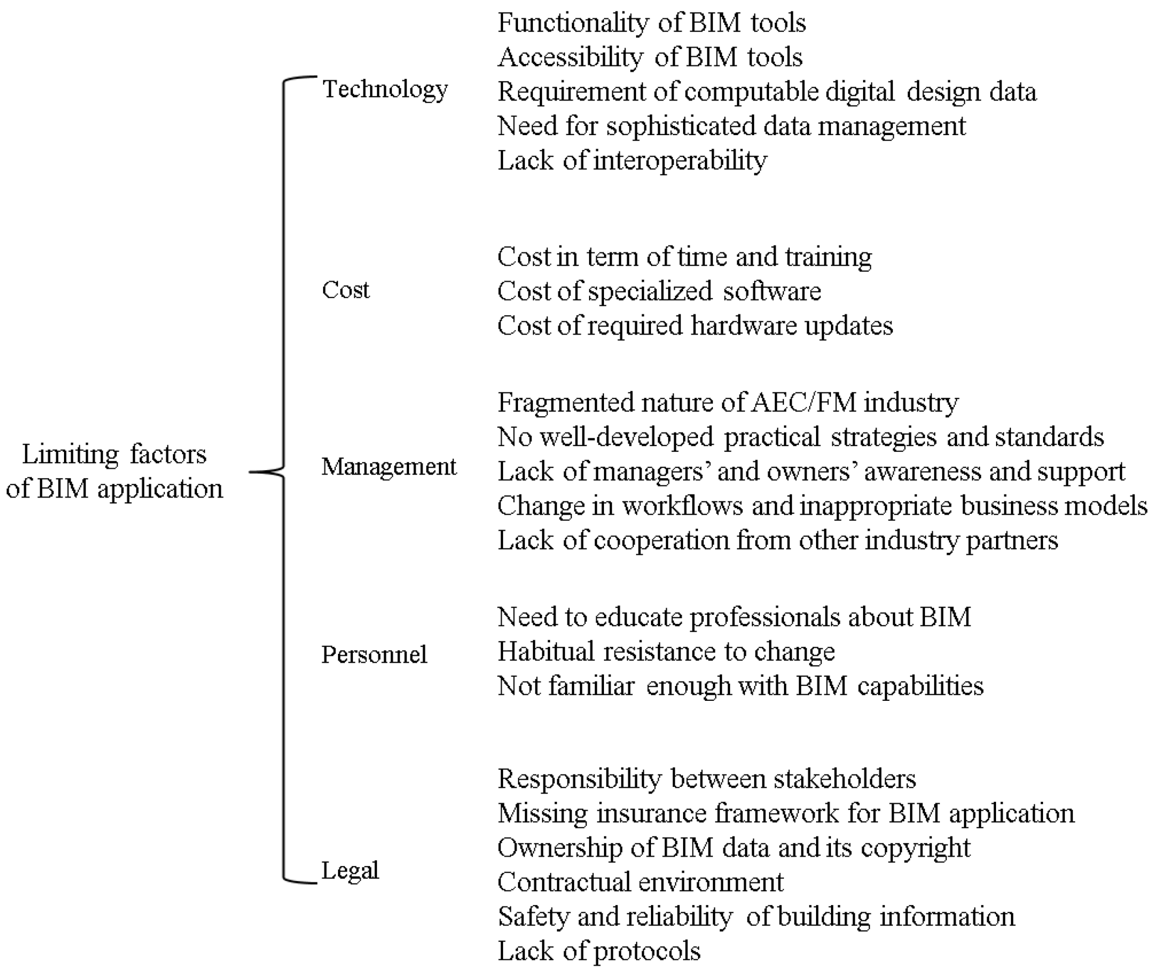


Figure 2-9 Factors limiting BIM applications (Sun et al. 2017)

2.3.2 BIM-based interoperability standards

Industry Foundation Classes (IFC)

BuildingSMART, previously known as the International Alliance for Interoperability (IAI), established a non-proprietary construction operations data model called Industry Foundation Classes (IFC). Their main objective is to provide a universal basis for process improvement and information sharing in the AEC/FM industry (East 2007). IFC is an object oriented data model with the aim to attain highest level of interoperability in AEC/FM industry on the level of data exchange (Svetel et al. 2014).

The main reason of using BIM is to increase communication among stakeholders through data interoperability during the facility's lifecycle. Even though there are a number of open BIM formats claiming to meet BIM requirements, IFC is considered as the most adopted interoperability data format in the AEC/FM industry and the major AEC/FM software development providers (WBDG 2018).

As a standard data sharing format, IFC offers all the proprietary software applications with a shared framework to save and exchange the facility information throughout its lifecycle (BuildingSMART 2018). IFC4 (formerly IFC2x4) is the latest version and it is still under improvement to incorporate more data linked to facilities lifecycle (WBDG 2018). IFC4 enables new BIM workflows including 4D and 5D model data exchanges, BIM to GIS interoperability, thermal simulations, and sustainability assessments. As sown in Table 2-1, Asen (2012) listed available modeling and management tools for AEC/FM industry and their main features and support for IFC.

IFC-based FM

FM departments need some tools to help in making the right decisions. Decision-support tools such as those suggested in the *Building Envelope Life Cycle Asset Management* project (Kyle et al. 2002) can provide standardized interfaces for asset managers (Lounis 1999). An IFC-based research project launched at the University of British Colombia aimed to implementing standards and defining transaction for data sharing and exchange within the AEC/FM industry. Information exchange can generally be described in terms of individual information transactions (Pouria and Froese 2001). There are several ongoing efforts to standardize the content of data exchange transactions without standardizing the transactions themselves. Standardizing the transactions will potentially provide better communication between users and increased productivity, which can reduce costs and control delays.

XML-based AEC/FM modeling standards

The eXtensible Markup Language (XML) is a simple text-based markup language developed by the World Wide Web Consortium (W3C) to assist information and services to be encoded with a meaningful structure that humans and computers understand (W3C 2018). XML has been also designed to ease interoperability with Hypertext Markup Language (HTML). The support of interoperability, simplicity, and extensibility of XML encourage the AEC/FM industry to develop and utilize several XML-based formats including LandXML, aecXML, gbXML and IfcXML.

Table 2-1 BIM tools for operation phase in AEC/FM industry (adopted from Asen 2012)

Product name	Vendor name	Main features	IFC support	Use in AEC/FM industry: Planning & design	Construction	Operations
Allplan Facilities Management	Nemetschek	FM	√			√
Archibus	Archibus, Inc.	FM				√
ArchiFM	Vintocon/GRAP HISOFT	Object-oriented approach, BIM-based facility maintenance modeling	√			√
ArTra BIM	CADPIPE	Interface to link 3D CAD			√	√
Dexter +Chaney	Spectrum Construction Software	Project management, construction accounting, equipment management and data sharing.				√
Field BIM (Vela Suite)	VELA Systems	Field BIM for construction	√	√	√	√
FM:Interact	FM:Systems, Inc.	FM				√
Glue	Horizontal systems	Web-based BIM management				√
Maximo	IBM	Asset management	√			√
Microsoft Dynamics	Microsoft Corporation	Construction project management				√
Project Document Manager	Joint partnership with McGraw Hill Construction	Create, publish, manage and distribute project information				√
Rambyg	MainManager	Web-based	√			√
Ryhti	OlofGranlund	Maintenance, planning and monitoring, request management and monitoring	√			√
Tririga	IBM	Space management, facility maintenance, and energy management	√			√
Vizelia	AXA	Space management, asset management	√			√

LandXML is an AEC/FM industry standard schema that allows exchange of data created during the surveying with all participants in the project. It is an open information exchange standard focused on modeling terrain, alignments and roads including a dedicated, independent geometry description format (Beetz and Borrmann 2018). This standard data format provides interoperability between different applications and is supported by many interested groups and organizations in the AEC/FM industry. Furthermore, it is also web-compatible, which allows participants to share data over the Internet.

AecXML was initially proposed by Bentley Systems in 1998 to satisfy the needs of the AEC industry. AecXML is an XML-based language capable of representing resources information such as projects, documents, organizations, materials, professionals, as well as processes or activities information, such as proposals, design, cost estimating, scheduling and construction. The aecXML schema is used for depicting all building data in design, engineering and construction disciplines (Svetel et al. 2014).

IFC Extensible Markup Language (IfcXML) is one of the most effective formats to transfer data to CMMS (BuildingSMART 2018). The IfcXML representation is an implementation of ISO-10303 Part 28 Edition 2 standard. This standard provides an XML schema specification that is an automatic conversion from EXPRESS representation of IFC schema (ISO 10303 Part 1). The mapping from EXPRESS to XML schema is guided by a configuration file that controls the specifics of the translation process. For IfcXML, this configuration file is standardized and published for each version of the corresponding IFC schema (BuildingSMART 2018). The output of this effort brought the new XML-based data representation (i.e., ifcXML). Recently, BuildingSMART released the final version of IfcXML for IFC4 Add2. Table 2-2 shows a comparison between IFC Express and IfcXML definitions. The relationships in IFC Express are defined using numbers (e.g., # 86). Each number refers to another IFC instance, which links the related components in the IFC model. In IfcXML, however, the relationship between nodes are defined as Parent-Child relationship in a hierarchy tree list, which is much easier to understand.

Table 2-2 Comparison between IFC Express and IfcXML (El Ammari 2006)

IFC format data sample	ifcXML format data sample
#84=IFCPROPERTYSINGLEVALUE ('Red',$,IFCINTEGER(255),$); #85=IFCPROPERTYSINGLEVALUE ('Green',$,IFCINTEGER(0),$); #86=IFCPROPERTYSINGLEVALUE ('Blue',$,IFCINTEGER(0),$); #87=IFCCOMPLEXPROPERTY ('Color',$,'Color',(#84,#85,#86));	<IfcComplexProperty id="i87"> <Name>Color</Name> <UsageName>Color</UsageName> <HasProperties> <IfcPropertySingleValue> <Name>Red</Name> <NominalValue> <IfcInteger>255</IfcInteger> </NominalValue> </IfcPropertySingleValue> <IfcPropertySingleValue> <Name>Green</Name> <NominalValue> <IfcInteger>0</IfcInteger> </NominalValue> </IfcPropertySingleValue> <IfcPropertySingleValue> <Name>Blue</Name>

The Green Building XML schema (gbXML*)* was initially developed to facilitate interoperability between design tools used in the AEC/FM industry. gbXML is integrated into a wide range of CAD-based modeling and engineering software. Additionally, with the development of integration modules inside major engineering analysis tools, gbXML has become their interoperability standard format. The most common data format for the exchange of building information between BIM and energy simulation tools such as *EnergyPlus* and *Ecotect* is the gbXML schema (Sokolov and Crosby 2011).

CityGML is a GIS standard developed by Special Interest Group 3D (SIG3D) and adopted as an official *Open Geospatial Consortium (OGC)* standard in 2008 (Deng et al. 2016). It is an XML-based encoding for the visual representation, data storage, and exchange of virtual 3D cities and landscape models. CityGML provides a standard model and mechanism for describing 3D objects with respect to their geometry, topology, semantics and appearance. Furthermore, its data format consists of georeferenced 3D geometrical data including façade textures and has different LODs (LOD 0 for regional level to LOD 4 for interior architectural models). In addition, CityGML is highly scalable for representing large-scale facilities such as airports, universities campuses, etc. Prandi (2015) discussed the development of 3D visualization of huge CityGML models on the web. Figure 2-10 shows an example of CityGML model of the city of Rotterdam.

Figure 2-10 CityGML model with texture of the city of Rotterdam (Prandi et al. 2015)

Construction Operations Building Information Exchange (COBie) is a specification that evolved from the idea of Computer Aided Facility Management (CAFM) (Schwabe et al. 2018). Crucial to the success of BIM and FMSs integration is a specific interoperability specification of the BIM data that is required for operations (Teicholz 2013). In recent years, there is a focus on COBie, the exchange format developed by the Corps of Engineers Research Lab for operational data handover (Sabol 2013). COBie uses a non-geometric subset of IFC, which can be extracted from IFC and transferred to Excel spreadsheets (Gelder et al. 2013).

2.4 MIXED REALITY TECHNOLOGIES

Mixed Reality (MR) is the merging of real and virtual worlds to produce new environments and visualizations where physical and digital objects co-exist and interact in real time (Drossis and Stephanidis 2018). Milgram (1999) introduced the MR continuum diagram (Figure 2-11) that defines the levels of augmentation. Besides the reality, the levels are extended to Augmented Reality (AR), Augmented Virtuality (AV), and Virtual Reality (VR). MR integrates a video-based or real view of the user's environment and some virtual contents within the same environment. Augmenting the real view with virtual contents is called AR, while augmenting the Virtual Environment (VE) with a part of the real view is called AV. In both visualization techniques, additional virtual contents (image, text or graphical model) can be superimposed and spatially attached to the relevant objects in the scene.

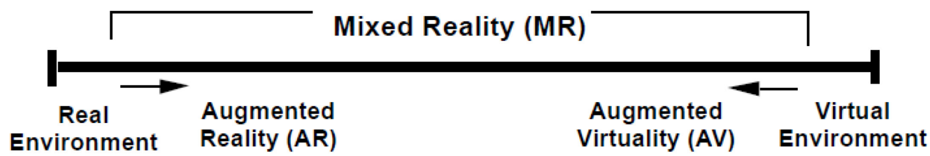


Figure 2-11 Reality-virtuality continuum (Milgram and Colquhoun 1999)

MR can extend the perception capabilities of the user in the real world and improve the interaction capability with the augmented objects, providing information that the user cannot detect personally and directly (Izkara et al. 2007). In addition, Gjøsæter (2012) presented a taxonomy of Handheld AR (HAR) applications. Zhou (2008) presented five main research areas in AR: (1) tracking techniques, (2) interaction techniques, (3) calibration and registration, (4) AR applications, and (5) display techniques. Each of these areas has requirements and the most challenging part is the calibration and registration, which can be expensive due to the lack of automated calibration methods.

Beyond AEC/FM research, MR is used in other areas, such as medicine, education, and gaming. Haouchine et al. (2013) superimposed computed tomography images on the laparoscopic view for surgery guidance. Their research explored the benefits of real-time augmented information for minimally invasive surgery. Also, Collins et al. (2014) overlaid a pre-operation Magnetic Resonance Image (MRI) on the laparoscopic view in uterine laparosurgery.

According to Kim et al. (2018), MR could be a good medium to replace or improve conventional telecommunication methods (e.g., video conferencing). As an example, Lincoln et al. (2009) developed telepresence systems using animatronic Shader Lamps Avatars and commodity depth cameras like Kinect sensors discussed in Maimone et al. (2011) for remote collaboration and telecommunication. Similarly, for a broadcasting scenario, Grundhofer et al. (2007) discussed an approach using an imperceptible coded image projected on a screen to achieve AR. They demonstrated the potential of this approach by adapting it for television studio situations.

2.4.1 Virtual reality technology

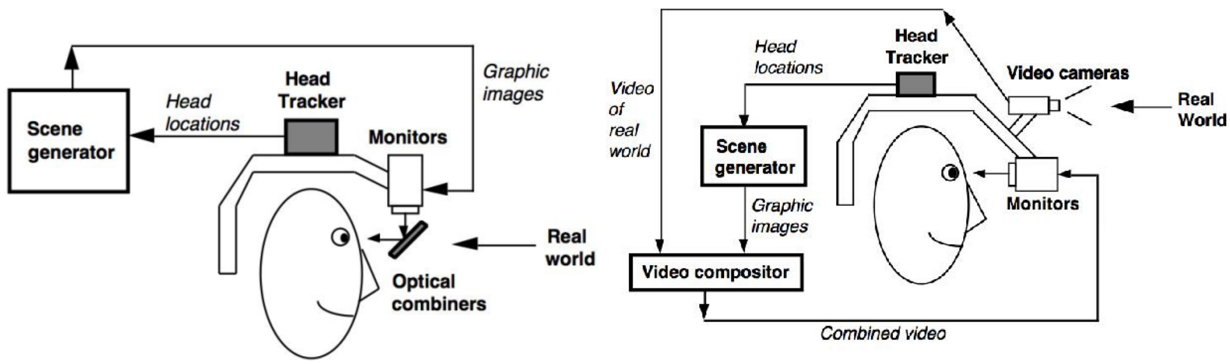
VR is a technology that builds a virtual 3D model in a computer to visually reproduce the shape, texture and movement of objects (Miyamoto et al. 2006). VR can be also defined as a computer-generated simulation of a real or imagined environment which a user can experience. Other virtual objects can be added in the virtual scene such as text objects, images and 3D sound effects. The main key features in using VR are: (1) The user believes that he/she is actually in the virtual world; and (2) The interaction capabilities with the model so that if the user moves his head, arms or legs, the shift of visual cues must be those he would expect in the real world. In other words, besides immersion, there must be interaction with the model. In addition, VR artificially create sensory experiences, which can include sight, touch, hearing, and smell. The VR technology became more mature and a number of companies showed interest in investing and developing VR Head Mounted Display (HMD) sets including Microsoft's Hololens (Microsoft 2018), Oculus Rift (Oculus 2018), and Samsung Gear VR (Samsung 2017).

2.4.2 Augmented reality technology

Augmented Reality (AR) is a visualization technology that integrates a real-time view of the user's environment using streaming video and virtual objects within the same environment. Figure 2-12 shows an example of using AR technology in urban planning. A roundtable is used as the base of the VR model and the users (urban planners) gather around it wearing HMDs and interact with the model using pointing devices (Ismail and Sunar 2009).

Figure 2-12 An application of AR in urban planning (Ismail and Sunar 2009)

Generally, HMDs can be categorized as the following: (1) Optical see-through HMDs, which are characterized by the ability to see through the display medium directly to the world surrounding the viewer; (2) Monitor-based HMDs, which are also called video, non-immersive Window-on-the-World (WoW) HMDs, refer to display systems where computer generated graphics are visually superimposed on the video images of the real objects (Milgram and Colquhoun 1999). Figure 2-13 shows a comparison between optical displays and video HMDs.



(a) Optical see-through HDM (b) Video HMD

Figure 2-13 Comparison between optical and video HMDs (Azuma 1997)

2.5 MIXED REALITY APPLICATIONS IN AEC/FM

The application of MR has been researched in different domains, such as in construction for supporting building inspection (Koch et al. 2012) , for proactive construction defect management using BIM (Park et al. 2013), for facilitating pipe assembly (Hou et al. 2013), for enhancing construction safety (Yabuki et al. 2013), for improving civil engineering instruction (Behzadan et al. 2018), for supporting the interaction of two users operating two virtual cranes and communicating with each other (Hammad et al. 2009), and for automatic construction progress monitoring (Golparvar-Fard et al. 2009). To improve collaboration, Wang et al. (2014) proposed a collaborative design system to enhance the distributed cognition among remote designers. Their discussion focused on how their system affects collaboration based on distributed cognition and mutual awareness. Irizarry et al. (2013) proposed a method for accessing building information through a situation awareness approach. A review of AR applications in AEC/FM was conducted by Rankohi and Waugh (2013). However, there are still issues related to the taxonomy of visualization (when, what, and how to augment) and collaboration (e.g., levels and types of interaction, immersion, telepresence) that need more investigation.

Whiskard et al. (2018) compared the current emerging MR tools and explored their potential in being applied to operation and maintenance of small and medium enterprises. Their research indicated that VR is best suited for visualization and collaboration tasks. However, the high cost and high pre-requisite data requirements may limit its applicability to enterprises. In addition, both AR and photospheres could be applied for locating building components, facilitating real-time data access and visualization tasks.

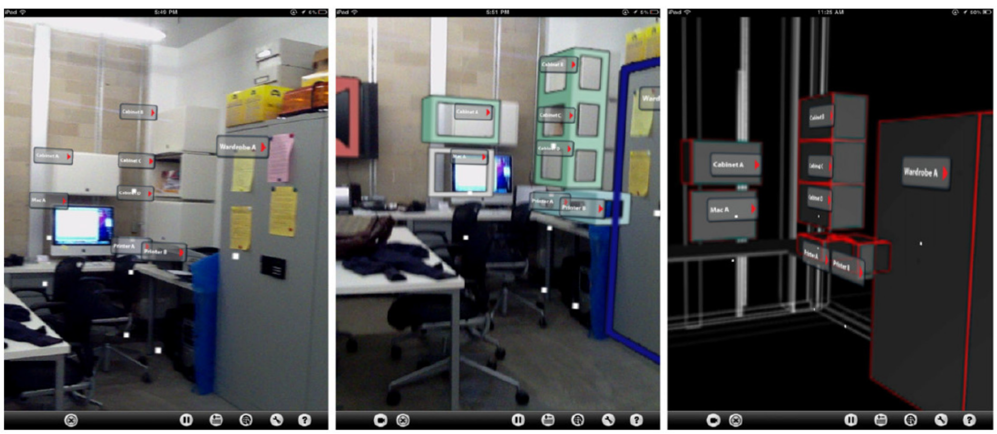
2.5.1 Visualization in MR-based AEC/FM applications

Although AR has been explored in AEC-related research for pre-design planning and analysis, and collaborative design, implementing AR as a visualization technique for FM projects during the operation phase is relatively new. Rankohi and Waugh (2013) have conducted a statistical review of recent AR-related research studies in AEC industry and the potential future trends in this area of research. Their research indicated that field workers and project managers have more interest in using non-immersive desktop AR applications during project construction phase for progress monitoring and detecting construction defects. Another study conducted by Dunston (2008) discussed the potential of AR applications in the AEC industry for several tasks including layout planning, positioning, inspection, coordination, excavation, supervision, commenting, and strategizing.

In the infrastructure management area, researchers have implemented MR to visualize underground utilities to facilitate utilities inspection and maintenance tasks (Roberts et al. 2002). Furthermore, an AR-based platform called Discrepancy Check developed by Georgel et al. (2007) allows users to see augmented information in order to spot the differences between an as-designed 3D model and an as-built structure.

Another research implemented MR to enhance visualization of subsurface utilities (Schall et al. 2010). The visualization capabilities of AR can be useful in facilitating inspection by enhancing the worker real environment with georeferenced context-related virtual objects. For example, Irizarry et al. (2013) developed a prototype called *Information Surveyed Point for Observation and*

Tracking (InfoSPOT) for accessing georeferenced facilities information using three visualization conditions. As shown in Figure 2-14, the three conditions are: (a) Augmented Reality I, where the real view is augmented with only textual information about the building component; (b) Augmented Reality II, where the real view is augmented with textual information and bounding boxes aligned with the target components; and (c) Virtual Model, where the user is shown a virtual model with textual information tagged to the target objects. During the experiment, the user is supposed to be stationed at a georeferenced mat (SPOT) and to rotate the tablet to look for pre-registered augmented information and interact with it. Even though the experiments showed high accuracy for the object alignment, which is one of the main issues in AR applications, InfoSPOT cannot work in mobile situations where the facility worker needs to navigate in the real environment and not just rotates at a fixed position.



(a) Augmented Reality I (b) Augmented Reality II (c) Virtual Model

Figure 2-14 InfoSPOT experiment conditions (Irizarry et al. 2013)

For remote visualization, Hoffmann et al. (2016) proposed a method that enables students to visit engineering laboratories remotely using a VR simulator. The simulator is used to emulate remote laboratories that can be located at arbitrary places away from their virtual replica. However, their research did show how students' knowledge can be increased using the VR representation of the remote engineering laboratories.

Object occlusions has been experimented in MR research, including visualizing of underground infrastructure (Schall 2011), handling method for ubiquitous AR using reality capture technology (Dong et al. 2011), and virtual excavation (Côté et al. 2014). These research efforts aimed to enhance the depth perception in AR. However, these efforts did not discuss the mobility aspects of the AR systems and how they affect the spatial transformation, as well as the visual perception of the occluded parts.

In addition, Behzadan and Kamat (2007) developed an AR framework called ARVISCOPE to visualize the simulation of outdoor construction operations and to facilitate the validation of the results generated by Discrete Event Simulation (DES). Another research effort was conducted to extend the use of AR to improve visual perception for excavation safety (Behzadan and Kamat 2009). In another example, Dai et al. (2010) presented an AR-based continuous quality monitoring method for piling construction by superimposing as-built drawings over site pictures.

Koch et al. (2012) presented a BIM-based AR framework for facility maintenance using unique registered natural markers to position the user. Based on the user pose (location and orientation), he/she will be provided with some information related to the building element along with 2D map for defining his current location and a guiding arrow to help him navigate in the AR environment. Their study showed the high potential of natural markers for AR-based FM system. However, due to the repetitive nature of buildings, creating a unique marker for each building element can be time-consuming. Figure 2-15 shows different AR views with (a) superimposed 3D navigation blue arrow and a virtual smoke detector position highlighted as a green box, (b) left turn instruction and same intact smoke detector, and (c) textual instructions shown at the bottom with the augmented small 3D animated instruction red arrows.

(a) (b) (c)

Figure 2-15 Supporting building inspection AR views (Koch et al. 2012)

2.5.2 Collaboration in MR-based AEC/FM applications

Milgram and Colquhoun (1999) introduced the MR continuum diagram which defines the levels of augmentation. Besides the reality, the levels are Augmented Reality (AR), Augmented Virtuality (AV), and Virtual Reality (VR). MR integrates the real view of the user's environment and some virtual contents. Augmenting the view with virtual contents is called AR, while augmenting the Virtual Environment (VE) with a part of the real view is called AV. In these visualization techniques, additional virtual contents (e.g., picture, text or graphical model) can be superimposed and spatially attached to the relevant objects in the scene. The application of MR has been researched in different domains, such as in construction for supporting building inspection (Koch et al. 2012), proactive construction defect management using BIM (Park et al. 2013), facilitating pipe assembly (Hou et al. 2013), improving students' performance in a building design project (Shirazi and Behzadan 2015), enhancing construction safety (Yabuki et al. 2013), improving design collaboration (Wang et al. 2014), and accessing building information through a situational awareness approach (Irizarry et al. 2013).

Collaborative systems have been used in the AEC/FM industry to support product design, maintenance and factory planning. BIM-based systems such as Revizto (Revizto 2018), AutoCAD 360 (Autodesk360 2018), and Bluescape (Bluescape 2018) allow site-office collaboration by sharing BIM and CAD drawings. The visual collaboration in these systems is limited to sharing 2D/3D views, documents and annotations about the facility components. However, collaboration in MR is relatively new due to the recent advancement of telecommunication technologies. Wang and Dunston (2011) mentioned that AR can reduce the mental disturbance in collaborative design tasks. Wang et al. (2014) proposed a collaborative design system to enhance the distributed cognition among remote designers. Their research focused on how their system affects collaboration based on distributed cognition and mutual awareness. Dong et al. (2013) showed that AR can facilitate engineering processes' communication. Similar research conducted by Datcu et al. (2014) led to the development of a system that supports situational awareness among team members in the area of security. In the same context, a remote assistance system called *ReMote* was discussed in Huang et al. (2013) to allow a remote expert to assist workers in a mining site. The remote expert views a real-time reconstruction of a remote workspace using a VR headset. Gauglitz et al., (2014) discussed the development of a tablet-based AR system that integrates a touch-based interface used by a remote user to tag real-world elements with annotations for supporting FM operations. Oda et al. (2013) introduced an AR-based remote collaboration system for supporting equipment inspection and maintenance. However, the visual collaboration presented in these research projects was done by sharing either the same view or the same model from different perspectives. This kind of collaboration is neglecting the fact that different users may have different interests in the data they want to access and interact with. These different interests can cause confusion and inaccuracy of data sharing during collaboration. In other words, being able to share ideas about what to do on a specific facility component by a field worker and a remote expert may improve visual collaboration and reduce inaccuracy of shared data that may lead to wrong decisions.

2.6 LOCATION TRACKING METHODS FOR INDOOR MR APPLICATIONS

In recent years, location tracking methods have received great attention in the area of pervasive computing because many applications need to know where the objects of their interest are located. Location tracking in MR applications has been discussed by several researchers. Normand et al. (2012) presented a typology of AR applications based on the tracking requirements. This research shows that the most challenging tracking issue in AR is the calibration and registration. In FM, an accurate estimation of the location and the orientation of the camera used for the MR is an essential step to estimate the camera pose and to correctly register the augmentation on the actual scene.

In general, tracking methods can be classified into two categories: sensor-based and computer vision (CV) based. In the sensor-based approach, several location tracking technologies have been investigated including the Global Positioning System (GPS), Wireless Local Area Network (WLAN), Inertial Measurement Units (IMU), Radio Frequency Identification (RFID), and Ultra-Wideband (UWB) Real-time Location Systems (RTLS) (Motamedi et al. 2013). According to Deak et al. (2012), UWB signals can pass through walls and offer higher accuracy. However, they are relatively expensive to integrate due to the high infrastructure cost. For indoor applications, GPS has low coverage (4.5%) (LaMarca et al. 2005). LaMarca et al. (2005) also indicated that WLAN has high coverage (94.5%) and less accuracy in indoor environments (15-20 m). In the CV-based approach, the tracking methods can be either marker-based using a registered printed marker or markerless-based (also known as feature-based) using registered natural features

(Rodriguez, R. M. et al. 2018). The marker-based method requires creating a large database of markers. The creation and the calibration process of these markers is time-consuming and requires accurate placement in the real world to achieve accurate and reliable tracking. In addition, supporting system mobility is important for FM applications, which eliminates the applicability of tracking methods that rely on RTLSs or marker-based CV approaches. In the feature-based tracking method, the detection is based on the features of the real environment and does not require markers. The feature-based method can provide acceptable tracking accuracy for MR-based applications supporting indoor FM operations. However, using feature-based tracking alone may not provide accurate and stable tracking for indoor MR applications. That is due to the lack of unique features or/and changes in light conditions.

2.6.1 Real-Time Location Tracking Systems

RTLSs are tracking technologies that detect and track the geolocation of a specified target. This target can be a moving car, an item in a manufacturing plant, or a person. Some of these tracking technologies can be used for indoor applications, where others can be more suitable for outdoor applications. For example, UWB and Wi-Fi positioning system (WPS) are more suitable for indoor applications because of their infrastructure dependency, whereas GPS is used for outdoor applications because it uses satellites signals. The accuracy for indoor tracking technologies is extremely important for critical applications where users need to locate items or themselves (e.g., safety). Figure 2-16 depicts a general overview of positioning systems (Liu et al. 2007).

The GPS is a satellite-based location tracking system based on a network of twenty-four satellites. The GPS receiver needs to receive signals from four satellites to get a position in 3-dimensions. Furthermore, GPS technologies consider the use of high-sensitivity GPS, which is appropriate for weak-signal environments (Schon and Bielenberg 2008) and Assisted GPS (A-GPS) with ability to send assisting information, such as satellite orbit information, to the receiver (Van Diggelen 2002), the weakness of GPS for indoor environment can be improved. The technology has been used by several applications including Locata (Barnes et al. 2003), U-blox (Thiel et al. 2007), and Atmel (Atmel 2017). For indoor applications, GPS has low user coverage indoors (4.5%) (LaMarca et al. 2005).

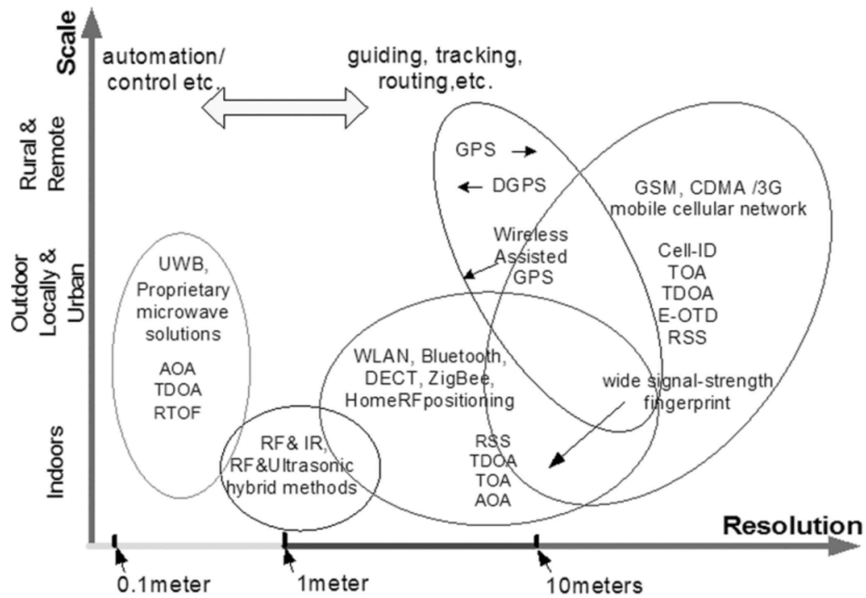


Figure 2-16 Comparison of positioning systems (Liu et al. 2007)

Wi-Fi positioning system (WPS) is often used for indoor applications where GPS is insufficient. The localization method used for positioning with wireless access points is based on measuring the intensity of the Received Signal Strength (RSS) and the method of *Fingerprinting* (Carboni et al. 2015). The location accuracy depends on the number of positions that have been received and stored into the database. Furthermore, the signal fluctuations that may occur can increase errors and then more inaccuracies in the path of the user. Georgiou et al. (2015) discussed *Anyplace,* which is an open Wi-Fi positioning system that allows users to map indoor spaces accurately (Anyplace 2018).

RFID use electromagnetic fields to track tags attached to objects. The tags contain digital information. There are two types of tags: (a) *Passive Tags* that collect energy from a nearby RFID reader's radio waves; and (b) *Active Tags* that have batteries and operate at hundreds of meters from the RFID reader. The RFID tags act as reference points for estimating the position of the reader which is used by the user (Papapostolou and Chaouchi 2011).

UWB is a wireless RTLS technology for transmitting large amounts of data over a wide range of frequency bands at low power, which is less than 0.5 milliwatts (Ghavami et al. 2007). In the last decade, several research efforts investigated the applicability of UWB in AEC/FM industry. For example, Zhang et al. (2010) and Rodriguez et al. (2010) have discussed the feasibility of tracking construction resources to improve productivity and safety on construction sites. Also, Teizer et al. (2007) investigated the usability of a UWB tag attached to a crane hook to track the position of the hook. Cho et al. (2010) discussed error modeling for an untethered UWB system for indoor asset tracking. Moreover, Giretti et al. (2009) indicated that UWB behavior is rather constant during most parts of the construction progress. According to Deak et al. (2012), UWB signals can pass through walls and offer higher accuracy. However, they are relatively expensive to integrate due to the high infrastructure cost.

2.6.2 Computer vision-based tracking

The existing tools for CV-based tracking offer the capability for using single camera or multiple cameras to have better location tracking. This allows MR application's users to use feature tracking based on multiple views (Côté et al. 2013). The CV-based tracking methods can be either marker-based tracking, using a predefined physical marker, or markerless-based tracking using natural features. In feature-based tracking, the detection of localized features from the natural environment can be done using the Scale Invariant Feature Transformation (SIFT) to estimate the camera pose for localization and tracking (Yuan 2006).

Feature-based tracking can be based on a single camera or multiple cameras to achieve a wider Field Of View (FOV), which positively affects the accuracy of the location tracking. According to Côté et al. (2013), this allows AR application users to allow feature tracking based on multiple views in a 360-degree view. To compare the CV-based tracking methods, the following section discusses in details both marker-based tracking and feature-based tracking techniques.

Marker-based Tracking

Marker tracking has been introduced for AR a decade ago. However, this technique is highly efficient in term of computational power and CPU usage and became more usable on handheld devices such as tablets and smartphones. There are two well-recognized marker-based tools for AR applications: ARToolKit (Khan et al. 2018) and ARTag (2009). These tools have been developed for video tracking of markers using a computer vision algorithm which calculates the camera position and orientation relative to the markers in real time. In these two systems, planar black and white images are used as markers. The pose of the marker is calculated and extracted from the live streaming video, and any virtual object associated with that marker is superimposed onto the video at its relative location with that marker. The main advantage of a marker-based tracking is that the markers can be designed in a unique way to ensure they remain relatively well-detected under different pose and lighting conditions. However, there are some disadvantages of marker-based tracking such as: (1) the registration process is time consuming; (2) the physical appearance of the markers that may not be acceptable; (3) mobility of the system requires mobile markers, which is not suitable for mobile engineering applications; and (4) short-range tracking capabilities because of the limited size of markers. Figure 2-17 illustrates the coordinate systems transformation used in marker-based tracking. T_{UM} is the relative position of the camera with respect to the marker in the marker coordinate system through a transformation, which can be provided by a tool such as ARToolKit. T_{MW} is the marker absolute location which is used to compute the transformation from the world coordinate system to the marker coordinate system. The outcome transformation T_{UW} is then calculated as the following:

$$T_{UW} = T_{UM} \cdot T_{MW} \qquad \text{Equation (2.1)}$$

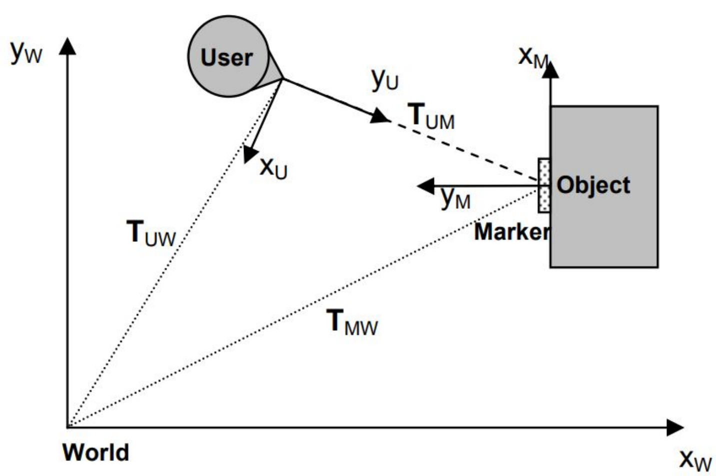
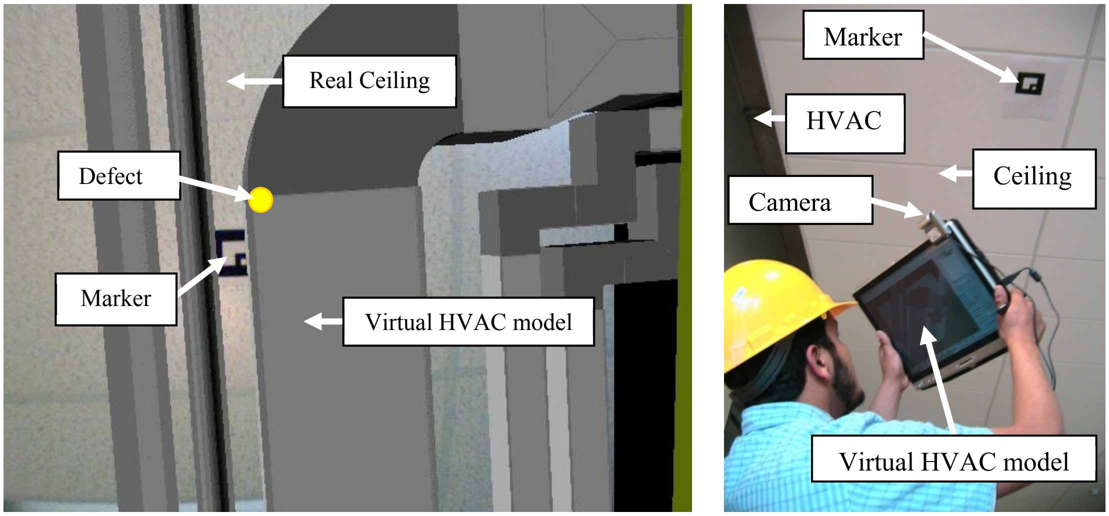


Figure 2-17 Computing user position using marker-based tracking (Hammad et al. 2005)

As an AR-based FM application, Figure 2-18(a) shows the view that the user shown in Figure 2-18(b) sees when the real ceiling is augmented with the virtual model of the HVAC system. The inspector's position and orientation are tracked and used to update the 3D view. The inspector can assign defects on the virtual model and retrieve duct element information.



(a) (b)

Figure 2-18 Inspector using tablet-based AR FMS (El Ammari 2006)

Feature-based Tracking

Feature-based AR system is an alternative to marker-based systems. In this system, the camera pose is calculated and extracted from naturally occurring features within the scene. It is suitable for engineering applications if a virtual object can be placed in a position relative to other objects within the scene without the need of using a physical marker as a reference. The Harris corner detector (Harris and Stephens 1988) and Lowe's SIFT detector (Lowe 2004) are feature-based detectors, which identify unique reference points within a stored image that can be computed in the correct position in other images. Furthermore, Li et al. (2004) introduced a system using trifocal tensors to place virtual objects as an augmentation by tracking points on natural features. In addition, feature-based AR has been introduced to AEC research by many researchers such as Bosché et al. (2012) and Côté et al. (2013). Their research indicates that feature-based AR is suitable for indoor environments with rich unique features where some conditions are controlled, such as the lighting conditions. To overcome the limitations in using CV-based tracking, Neges et al. (2017) presented a method that combines an IMU-based step counter and visual live video feed for AR based indoor navigation support. They compared the current indoor navigation approaches as shown in Table 2-3.

Table 2-3 Comparison of indoor navigation approaches (Neges et al. 2017)

Approach	Evaluation criteria			
	Additional IT infrastructures required	Data preparation effort	Continuous positioning	Accuracy
WLAN	– Specific infrastructure installation	○ Signal measurement at reference points	+ Depends on signal coverage	○ Building-specific disruptive factors
RFID	– Specific infrastructure installation	○ Signal measurement at reference points	+ Depends on signal coverage	○ Building-specific disruptive factors
Indoor-GPS	– Specific infrastructure installation	++ None	+ Depends on signal coverage	+ Building-specific disruptive factors
3D-Maps/SLAM	+ 3D scanner for initial data creation	–– Cleaning recorded point clouds	+ Depends on point cloud quality	+ Depends on point cloud quality
IMU	++ High availability of integrated IMU	++ Realtime	++ Permanently	– High error propagation
Natural marker detection	++ Natural markers already present	+ Required information already exist in BIM	– Only at detection	○ Depends on light condition
Proposed solution IMU + natural marker detection	++	++ Realtime by IMU	++ Permanently by IMU	+ Stored light condition for each marker position

++ very good/positive; + good/positive; ○ average; – poor/negative; –– very poor/negative.

2.7 SUMMARY

According to the conducted literature review, FM management practice is evolving due to the technology advancement. Utilizing and adopting emerging technologies such as BIM, MR, and tracking technologies may improve productivity and efficiency of FM tasks. However, even though BIM seems promising to improve interoperability and data communication between stakeholders, the amount of geometric data become less important during the FM phase to perform field tasks. That is because of its complexity, which makes it harder to navigate, select, and update information of the right facility component. On the other hand, MR has a great potential to improve visual communication and collaboration. Using CMMSs in a mobile AR-based setting helps field workers to focus on the actual inspection or maintenance task rather than getting busy with the complexity of the facility model. However, facilities managers look at BIM and MR differently. They are almost interested in every detail in the BIM model including geometrical and non-geometrical data such as materials, cost, schedule, etc. Thus, they need VR as visualization technology since they are dethatched from the remote inspection or maintenance site. For that reason, MR seems to be a good candidate as visualization technology, where collaboration of two stakeholders is possible and both can work together using different visualization environments that fit their different needs. Furthermore, there are several affordable tracking technologies that can be utilized for mobile MR-based CMMS. To conclude, the literature review shows that CMMSs in the current practice lack functionalities to support mobile filed tasks and task collaboration with the remote office.

MR has been used in FM in mobile and stationary modes, as well as for indoor and outdoor scenarios. These scenarios provide good understanding of the MR requirements to satisfy the user needs and the task requirements. Based on the review discussed in this chapter, there are many components that need to be defined either as input or as output components. The input MR components can be classified into three main categories: (1) MR contents; (2) Tracking input; and (3) Interaction devices. Figure 2-19 shows the taxonomy of all MR components based on input/output classification. The right side of the same figure lists the main four augmented output categories and their components that can be sensed directly by human natural senses: sight, hearing, touch, and smell.

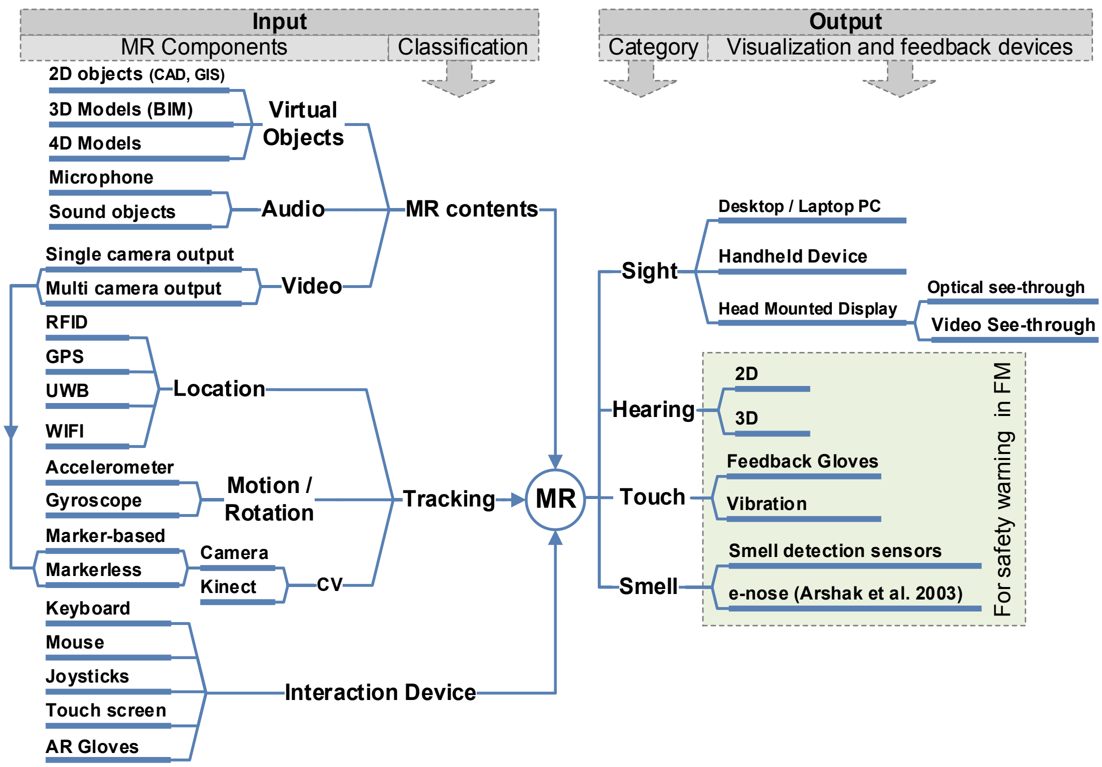


Figure 2-19 Taxonomy for MR components for FM (El Ammari and Hammad 2014)

Table 2-4 summarizes the related research efforts and compares them based on four categories: (1) Data integration using BIM, georeferenced contents, sensory data, and scalability of the data; (2) Tracking method (i.e., support for system mobility and users' telepresence); (3) Visualization methods; and (4) Collaboration type. Even though there are serval research projects investigating collaboration, there are still a number of limitations including the remote interaction considering the different interests of task and the facility information for each stakeholder.

Table 2-4 Comparison of recent research efforts related to MR applications in AEC/FM

Paper	Support: Integrated Data				Tracking		Visualization			Collaboration		
	BIM	Georeferencing	Sensory data	Scalability	Telepresence	Mobility	Augmented Reality	Virtual Reality	Guidance	Data Sharing	Remote Collaboration	Real-time Interaction
Integrating mobile building information modelling and augmented reality systems: an experimental study (Chu et al. 2018)	√					√	√					
Mixed-Reality for Object-Focused Remote Collaboration (Feick et al. 2018)							√	√	√	√	√	
Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making (Du et al. 2018)	√							√				√
Precision study on augmented reality-based visual guidance for facility management tasks (Liu and Seipel 2018)	√					√	√		√			
BIM based Multiuser Collaborative Virtual Environments for end user involvement (Sørensen and Svidt 2017)								√		√		
A study on software architecture for effective BIM/GIS-based facility management data integration (Kang and Hong 2015)	√	√	√									
Mutual awareness in collaborative design: An Augmented Reality integrated telepresence system (Wang et al. 2014)					√		√			√	√	
Collaborative visualization of engineering processes using tabletop augmented reality (Dong et al. 2013)							√	√		√		
A mobile Augmented Reality method for accessing building information through a situation awareness approach (Irizarry et al. 2013)	√	√					√	√				
Comparative effectiveness of mixed reality-based virtual environments in collaborative design (Wang and Dunston 2011)							√			√		
Current thesis	√	√	√	√	√	√	√	√	√	√	√	√

CHAPTER 3 OVERVIEW OF THE RESEARCH FRAMEWORK

3.1 INTRODUCTION

As a first phase of the research methodology, the literature review is conducted to identify the research gaps and to define the research objectives. The scope of this research is finding methods to improve tracking, visualization and collaboration in MR-based FMSs. Figure 3-1 summarizes the research methodology. The literature review indicated that current CMMSs lack visualization and collaboration functionalities that are required to facilitate FM field work. Based on this finding, a general framework is discussed in this chapter followed by the tracking, visualization and collaboration methods, which are introduced and discussed in Chapters 4 and 5, respectively. Chapter 6 is the implementation where a prototype system is developed and tested through a case study using a usability testing.

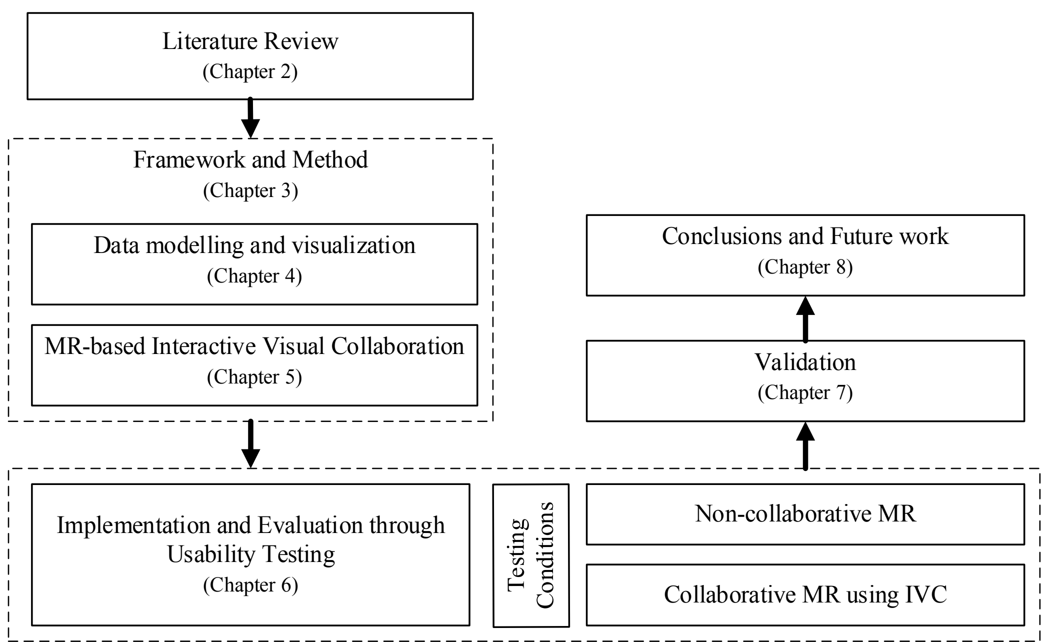


Figure 3-1 Research methodology

Based on the system architecture introduced in Section 3.6, a prototype system is developed and the implementation process is discussed in Section 6.4. The system is called Collaborative BIM-based Markerless Mixed Reality Facility Management System (CBIM3R-FMS) and it has two modules: (1) AR module for the field worker and IAV module for the facility manager. The users test the system based on two testing conditions: (1) non-collaborative MR, and (2) collaborative MR. After performing the assigned tasks, the users answered a usability questionnaire. The next phase involves the analysis of the collected testing data using Analysis of Variance (ANOVA) which is discussed in Chapter 7. The final phase is concluding the results with recommendations for future work (Chapter 8).

3.2 INSPECTION PROCESS RE-ENGINEERING

To minimize the chances of getting data collection and entry errors, it is important to re-engineer the data collection process applied in CMMSs by allowing more automation using MR. In addition, it is important to consider all subtasks during the inspection process for both the facility manager at the office and the field worker. Figure 3-2 shows the main steps involved in performing an inspection task by both the field worker and the facility manager. These demanding subtasks require extra attention to avoid unnecessary mistakes during data entry or data re-entry at the office.

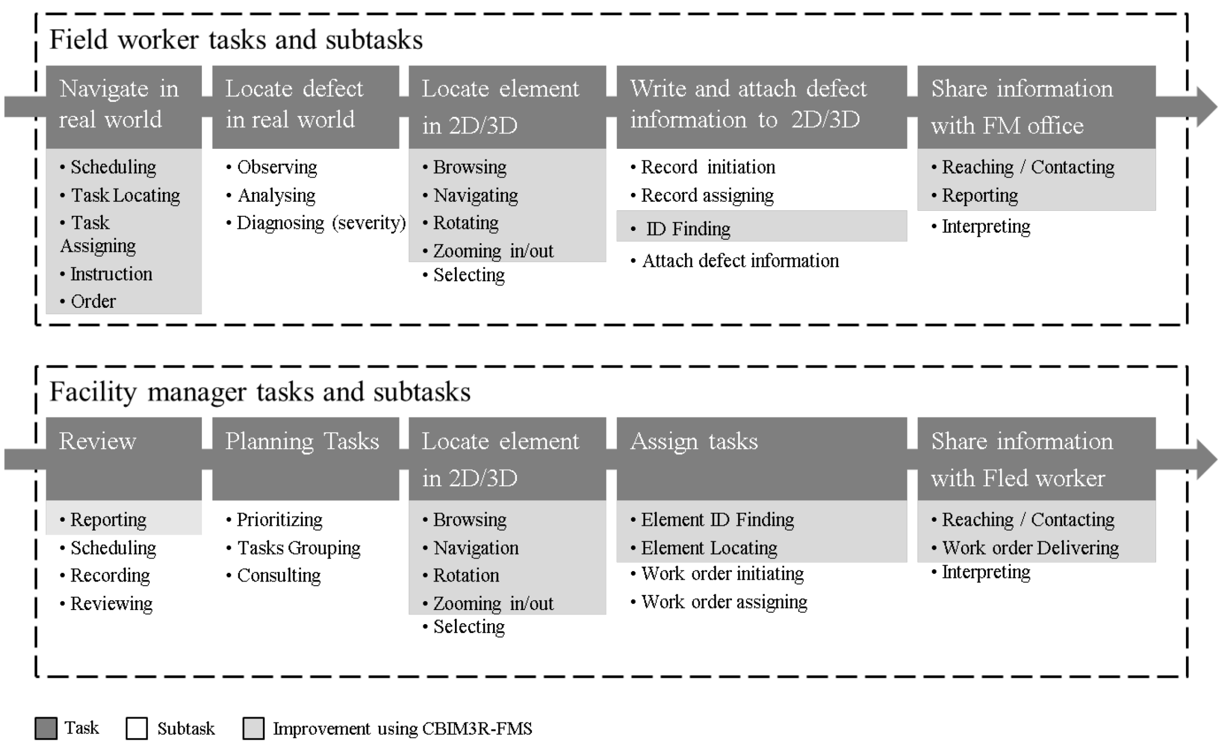


Figure 3-2 Inspection processes subtasks automation

The subtasks highlighted in gray can be fully automated. The automation of these subtasks can improve productivity of FM field tasks by avoiding data collection errors and saving time for data entry. These subtasks (e.g., browsing for specific element) require special attention to avoid mistakes during data entry or data re-entry at the office. Most of these subtasks are currently done manually by the users; and it is expected that automation of data collection with improved visualization can partially solve these issues. Subtasks that require first identifying the building element can be fully automated based on the field worker location and orientation.

For more collaboration support between the field inspector and the manager, an MR-specific inspection process reengineering is investigated, as shown in Figure 3-3. After reviewing the defects records, the facility manager assigns work orders to the field workers. Since the defects are all georeferenced, the facility manager is able to assign tasks after he/she grouped them based on their locations. Each record consists of the task ID, field worker ID, task type (e.g., replacing a thermostat), date and time of the assigned task, and tools needed to perform the task. The defect coordinates are used to position the task tag in both the AR and the IAV environments. Using these coordinates also allows the field worker to access extra information about the assigned task from the Defect database.

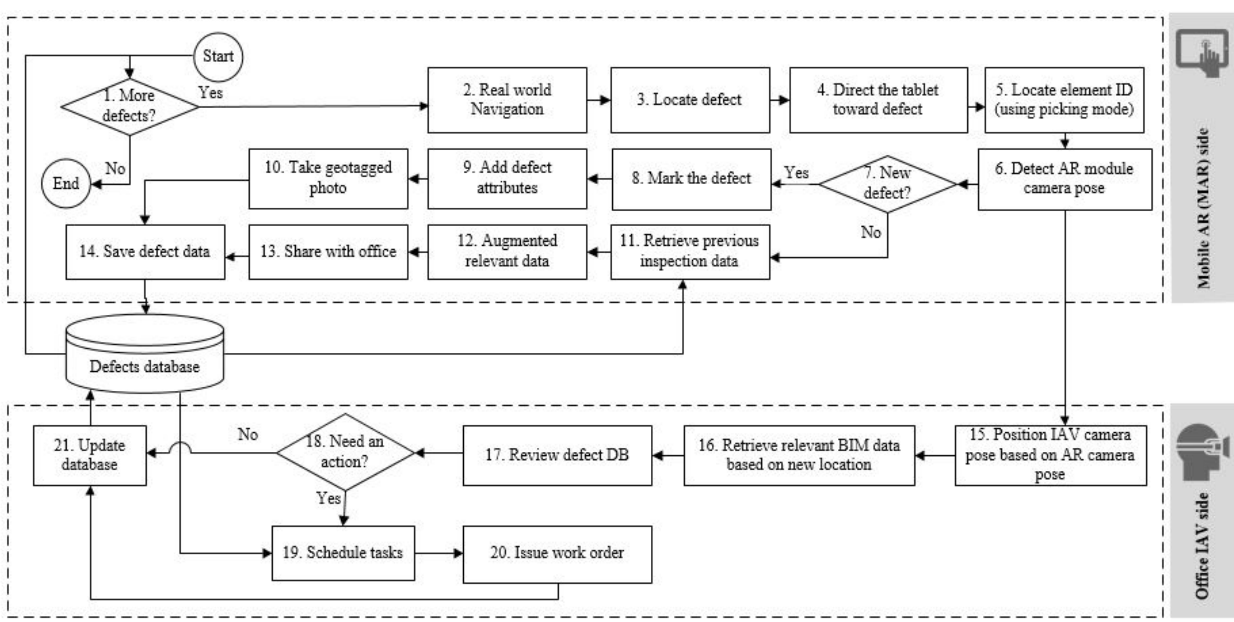


Figure 3-3 Flowchart of detecting and marking defects in CBIM3R-FMS

Mobile AR module processes

The detection and marking of a defected building element start with the inspector walking around the facility for routine or scheduled inspection. At first, the field worker checks if there are new inspection work orders. If there is an inspection task assigned (as explained in the next section), the field worker navigates to the target location guided by the rendered path and directed by the guidance arrow. Once the field worker reaches the target location, he/she observes and locates the defect in the real world. Then, he/she directs the tablet toward the located defect keeping a perpendicular relation with the defected element (e.g., a wall), which is important to facilitate picking and marking the defect in AR module. Using the picking functionality, which is based on *ray tracing method*, the field worker picks the location of the defect on the element through the AR view. The AR module detects the camera pose based on the hybrid tracking method, which is explained in Section 4.2.1. The field worker then checks if the defect is new by retrieving the element information from the *BIM* and the *Defect databases*. If the defect is new, the field worker marks the defected area using a color-coded symbol (e.g., red sphere). The field worker adds the defect attributes including the type, severity, and other inspection notes. At this stage, the field worker may add a picture of the defect and store it in the *Defect database*. The defect picture is geotagged with the pose information. This information can be used to position the picture in the IAV module to assist the facility manger to make better decision about evaluating the problem or planning for fixing the defect. Optionally, the AR module camera view can be streamed to the IAV module as a correctly positioned scaled window as discussed in Section 4.4.2. This step allows the facility manager to compare the virtual and the real views to enhance his/her perception of the defect condition. If the defect is an old one and it has information in the *Defect database*, the AR module retrieves previous inspection data related to this defect and augments it on the AR view to allow the inspector to re-evaluate or update its record. Whether the detected defect is a new or an old defect, its information is saved in the *Defect database*.

Office IAV module processes

As shown in Figure 3-3, Once the AR module camera pose is detected (at step 6), the IAV virtual camera pose is repositioned based on streamed AR module pose information. The facility manager can retrieve in real time all inspectors' locations, which helps him/her to assign tasks based on the location and availability of the field workers. The nature of the manager duties requires reviewing, scheduling, monitoring, and then assigning inspection and maintenance work orders. Therefore, the facility manager is required to collaborate with the field workers to be able to update and manage FM operations of the facility. Based on his/her current pose in the VE, the facility manager can retrieve the relevant BIM data and defects records. At this stage, the facility manager should make a decision about if any action is required (e.g., redo the inspection because some information is missing). If an action needs to be done, then he/she should schedule a new task. Based on the scheduled task and the availability of field workers and other inspection tools, the facility manager issues a new work order. At the end, the facility manger updates the *Task database* whether an action is required or not.

3.3 CBIM3R-FMS SYSTEM MAIN FUNCTIONALITIES

The Collaborative BIM-based Markerless Mixed Reality Facility Management System (CBIM3R-FMS) introduced in Section 3.1 has multiple functionalities. Based on the process re-engineering explained in Section 3.2, the functionalities are: (1) pose tracking and navigation support, (2) task allocation, (3) visualization, (4) interaction, (5) sensing, and (6) collaboration.

(1) Pose tracking and navigation support: The pose tracking is necessary for accurate aligned augmentation and interacting with the VE components in both the AR and IAV modules. The pose tracking in the AR module requires accurately tracking the location and orientation of the field worker camera in the AR module. This research uses three tracking methods to facilitate this functionality as explained in Section 4.2. The pose information of the field worker is used to adjust the pose of the virtual camera in the IAV module. In the IAV module, the head orientation of the facility manager is tracked using embedded sensors in the VR HMD and is used to update the AR module view, using arrows, with his/her view of interest. There are two types of navigation. In the first type, the facility manager navigates in the VE supported by the navigation functionality, which has two modes: (1) The constrained mode, and (2) The free mode. In the constrained mode, the facility manager virtual camera pose in the VE is adjusted based on the AR module camera pose information. The constrained mode is only used before starting the IVC, as explained in Section 5.2, to locate the facility manager in the VE. Once the virtual camera pose is updated, the system switches automatically to the free mode. In the free mode, the facility manager can navigate freely in the IAV using the navigation hardware (e.g., VR controllers).

(2) Task allocation: The facility manager assigns the tasks to the field workers using the IAV module. Assigned tasks are georeferenced using 3D objects (e.g., a blue cube). The facility manager can use different shapes and colors to differentiate between task types (e.g., routine inspection vs. reported defect inspection) and between task priorities (e.g., urgent vs. regular). The task allocation relies on different data sources including the location of field workers, inspection reports, schedule, and work order records.
(3) Visualization: Visualization relies mainly on the rendering methods, which include object texturing, lighting, and occlusion. The two modules of the system have different requirements to support visualization, which are explained in Section 4.4. Capturing and collecting defect and task-related data is an important functionality of CBIM3R-FMS. Sensing is one functionality of the system that facilitates data collection, which eventually supports decision making. For example, providing a thermal image can support decision making by comparing it with the real view and with BIM data.
(4) Interaction: In the IAV module, the facility manager is immersed in the VE and he uses two types of interaction: (1) Interaction with the facility components using a virtual pointer based on ray tracing technique; (2) Interaction with MR-based GUIs. In both methods, the interaction is done using VR controllers and gesture-based interaction. In addition, the Interaction with the VE has different modes including the object manipulation and GUI manipulation. The object manipulation involves object selection, moving, adding, and coloring.
(5) Collaboration: This functionality is responsible of opening a channel of IVC between the IAV and AR module users. The IVC method allows CBIM3R-FMS users to collaborate in real time while sharing their views to discuss and make appropriate decisions. For better communication between the field worker and the facility manager, the both modules are connected with audio and text chatting channels.

3.4 PROPOSED FRAMEWORK

The proposed framework consists of two main parts. First, data integration part is required to build the georeferenced VE from several sources including BIM, Geographic Information Systems (GIS) and City Geography Markup Language (CityGML) (discussed in Chapter 4). Second, the interaction part between the office manager and the field worker in CBIM3R-FMS is developed as shown in Figure 3-4, which is discussed in details in Chapter 5. The framework supports two types of activities: (1) Activities of the facility manager where the routine FM work is performed including the review of work orders, scheduling and assigning inspection and maintenance tasks, and supporting field workers using the IAV module; and (2) Activities of the field worker (e.g., inspector) who uses a tablet to perform the assigned task in the AR-based module and collaborate with the facility manager in real time. The facility manager, using VR headset, is immersed in the VR facility model and he/she is able to interact with the BIM-based facility components and with the field worker in real time. The field worker uses tablet-based AR module that allows him/her to interact with the real environment by retrieving georeferenced facility data, and to collaborate with the remote office by adding georeferenced annotations. The databases are used to add, update, and retrieve task-related data.

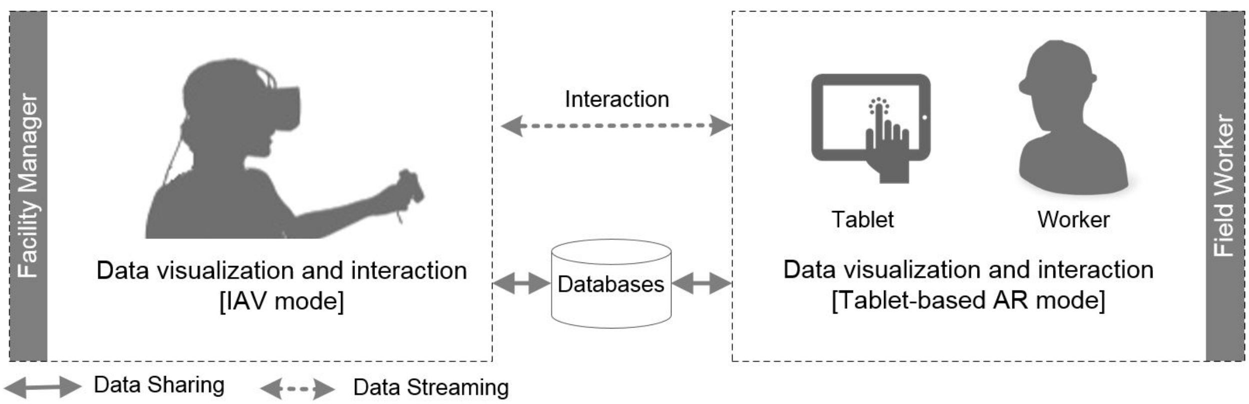


Figure 3-4 Interaction between office manager and field worker in CBIM3R-FMS

CBIM3R-FMS requires using georeferenced BIM-based facility data, which is important for FM task collaboration because the field worker should know his/her relative location with respect to the target element to apply the augmentation. At the same time, the facility manager should know both the target element and the field worker locations to know how to assign and support tasks.

To explain the CBIM3R-FMS framework, the following section (Section 3.5) discusses the data pre-processing and the four databases creation method. Section 3.6 discusses the CBIM3R-FMS system architecture. Section 5.2 discusses the MR-based Interactive Visual Collaboration (IVC) method. The interaction modalities for the two modules are discussed in Section 5.4.

3.5 DATA PRE-PROCESSING FOR CBIM3R-FMS

As shown is Figure 3-5, there are four databases which are connected with the two modules of the system. The databases are: *Tracking database*, *BIM database*, *Defect database*, and *Task database*. During the pre-processing phase, feature-based tracking requires collecting large number of images within the building in order to detect the features that will be used for tracking. The field worker has the role of building and feeding the databases with the relevant information. First, he/she is responsible of collecting the images, which will be used to create the feature-based tracking data. Then, he/she is responsible of collecting defect data and storing them in the *Defect database*. On the other hand, populating the *Tracking database* should be done at the office by processing the collected images and 3D models of the building to create the feature-based tracking data. The BIM models should be created and saved in the *BIM database*. In addition, the facility manager updates the *Task database* based on the inspection reports, records and schedule. The pre-processing data workflow is as the following:

(1) The images should be collected by the field worker.

(2) BIM-based modeling is done at the office, which can be newly created or updated models. The BIM data are saved is an IfcXML format in the *BIM database*. The IfcXML format is suitable for non-geometric data retrieval and exchange using an Extensible Markup Language (XML) parser. The database hierarchical structure inherits the structure of the IfcXML main nodes. For example, if the facility consists of a number of buildings and each building has many floors, the database will have the same hierarchy to facilitate data retrieval during real-time operations.

(3) The collected images should be processed including the registration of the CV features by mapping them with the BIM model to generate tracking data. The tracking data are saved in the *Tracking database*.

(4) The VE is created based on the BIM models, which will be used in the IAV and AR modules. Furthermore, CityGML allows creating models with different Levels of Detail (LOD) for large 3D environments. CityGML data are used as the base model for CBIM3R-FMS. The 3D multisource data integration is processed and the result is transferred to a data format that keeps the necessary information including elements IDs and the hierarchy structure of the original model (e.g., Autodesk FBX technology). It is important to keep both the structured

3D data and the IDs to integrate with the BIM-based attribute database. The implementation of processing BIM model is discussed in Section 6.3.1.

(5) The task scheduling is done by the facility manger, where he/she should update the *Task database* with task-related information including task ID, scheduled date, and assigned location, worker, and tools.

(6) Detected defects by the field inspectors are stored in the *Defect database* including geotagged defects images and descriptive textual information about the defects. During the operations, since the field worker pose is tracked using the location and orientation of his/her tablet, he/she will be able to take geotagged pictures of the potential defects and automatically send them to the office. The images will be positioned at their relative positions in the VE. This will allow the facility manager to initiate the work order and assign it to the suitable inspector.

Moreover, the conditions of components are updated to reflect the work done by inspectors and technicians according to the preventive and corrective work orders. The updated data from the system can be retrieved and visualized using defined queries for visual analytics. In addition, new defect-related attributes, required for FM, are added to the *Defect database*.

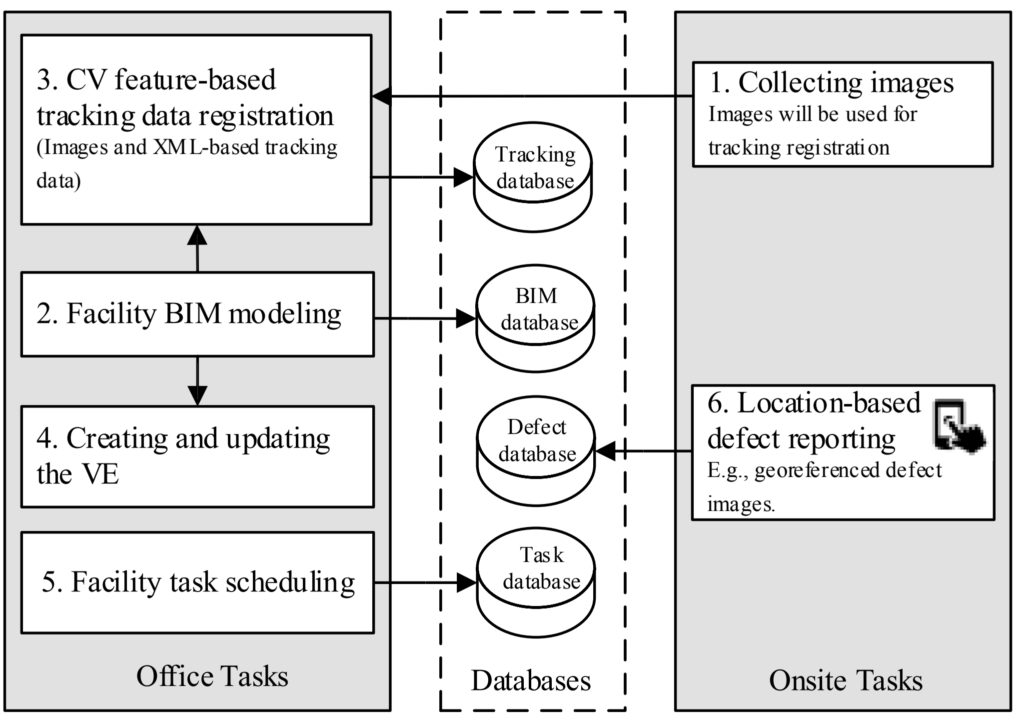


Figure 3-5 Pre-processed data for CBIM3R-FMS

3.6 CBIM3R-FMS SYSTEM ARCHITECTURE

Based on the aforementioned general framework, Figure 3-6 illustrates the system architecture, which consists of three parts: (a) FM office IAV module, (b) field worker AR module, and (c) the databases. The dataflow between these components is explained in the following:

(1) On the IAV office side, the facility manager reviews work orders and schedules inspection or maintenance tasks. The manager starts assigning georeferenced inspection or maintenance tasks by pinpointing in the VE and selecting components. The task assigning could be based on the selected space (e.g., room) or element (e.g., wall). The selected component can be highlighted with colors to define the priority of the work orders. For example, red is used to indicate high priority, orange for moderate priority, and yellow for low priority. The task data, including location information, are saved in the *Task database*.

(2) The video from the tablet camera is used for feature-based tracking. The video frames are used to detect the relevant features and retrieve them from the *Tracking database*. The tracking is activated based on the detected features.

(3) The embedded orientation sensors in the tablet feed both the mobile AR side and the office IAV side of CBIM3R-FMS with pose tracking data. On the mobile AR side, these tracking data can support the CV-based tracking when no registered features are detected. The tracking data of the tablet are streamed to update the pose of the virtual camera of the IAV module. As explained in Section 3.2, the matching of the two modules' camera pose helps each user to identify the other user point of interest, which is scoped by the camera Field of View (FOV).

(4) The current position of the field worker and the georeferenced tasks' location information are used to update the direction of the navigation guiding arrow as an augmentation to help the field worker navigate his/her way to the task location. Based on the pose of the tablet camera of the field worker, basic information about the task is retrieved from the *Task database* and augmented over the view of the real building element.

(5) The field worker can select an element by picking the real element through the AR view and retrieve additional BIM information from the *BIM database*. The picking is initiated based on a raycasting method (Wu et al. 2018), and the unique ID from the geometrically optimized model, as discussed in Section 6.3.1, is used to retrieve relative data from the database. Once the element is identified in AR, the field worker can add or modify inspection or maintenance

information. This information can be geotagged images or textual information. The resulting data will be saved in the *Defect database*.

(6) The defect data stored in the *Defect database* including building elements, and elements IDs are used to update the AR module view.

(7) Based on the required task, the facility manager updates the BIM model. For example, if the required task is making an opening in a drywall, the BIM model is modified by the facility manager, using a BIM tool, and then the modified model is used to update both the AR and the IAV views. The facility manager retrieves the updated task data and starts collaborating with the field worker by augmenting the mobile AR view with his/her comments and interactive pointing and sketching.

(8) Extra sensory data, such as thermography images captured by an infrared (IR) camera, can add an additional layer of information to the augmented scene about the condition of the facility components, and help the inspector detect the source of the problem (e.g., water leakage inside the drywall).

(9) The field worker can share his/her AR module view with the manager to help him/her better diagnose the element condition since the manager has more experience. This view will be shown in IAV mode.

(10) The manager collaborates with the field worker using virtual pointing arrows to guide him in real time and discuses, if needed, any task related matters. This allows both users to be aware of each other's point or area of interest. The system also supports audio and text-based chatting to facilitate real-time communication.

The MR-based IVC helps both the field worker and the facility manager to visually communicate with each other and share the necessary information related to the assigned task. The mobile AR-based module helps the inspector to visualize the captured sensory data (e.g., the IR picture), mark the detected defect, and review elements inspection history. On the other hand, the office IAV allows the manager to guide the field worker where to go, share what he/she sees in his/her rich model, and perform tasks that require more experience. For instance, the facility manager can help the field inspector in assigning the defect severity and discuss about potential elements that require further inspection.

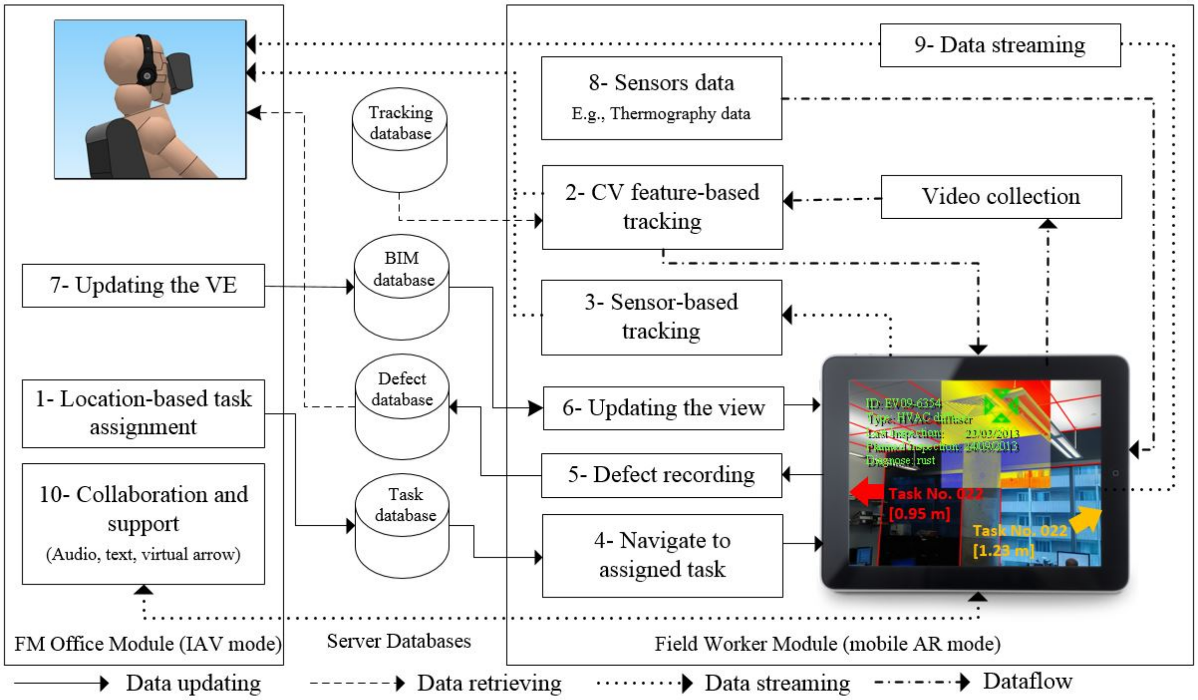


Figure 3-6 System architecture of CBIM3R-FMS

3.7 SUMMARY

This chapter discusses the research methodology and workflow. After discussing the inspection process re-engineering, the main functionalities for the prototype system are presented. These functionalities include pose tracking and navigation support, task allocation, visualization, interaction, and collaboration. The general framework and a brief description about the prototype system (i.e. CBIM3R-FMS) are discussed. The framework is introduced as general framework which provides data integration and visualization methods. These methods are discussed in Chapter 4. The framework also describes the requirements of the remote interactive visual collaboration between the facility manager at the office using IAV module and the field worker using AR module as explained in Chapter 5.

Furthermore, the data pre-processing is discussed including the facilities' *BIM database*, *Tasks database*, *Defects database*, and *Tracking database*. The creation of the databases and the role of the different users are explained. Finally, based on the required functionalities of the framework, a full description about the system architecture is provided.

CHAPTER 4 ENHANCING TRACKING, MODELING AND VISUALIZATION IN MR-BASED FACILITIES MANAGEMENT SYSTEMS

4.1 INTRODUCTION

To satisfy the requirements of Collaborative BIM-based Markerless Mixed Reality Facility Management System (CBIM3R-FMS) introduced in Chapter 3, data modeling and visualization are essential for better Interactive Visual Collaboration (IVC). Based on the CBIM3R-FMS framework introduced Chapter 3, the remote IVC between the facility manager at the office and the field worker can be done using two wirelessly connected modules: (1) AR module used by the field worker and (2) Immersive Augmented Virtuality (IAV) module used by the facility manager at the office. Based on the literature review, choosing AR as a visualization technology for field worker module is to minimize the amount of visual data that he/she wants to deal with and focus more of performing the task with only task-related data. On the other hand, allowing the facility manager to work in a virtual environment with extra data streamed from the field is a necessary step to improve his/her awareness about the task area context. As discussed in Chapter 3, both modules interact with the same databases and with each other using the IVC method. The framework supports two types of activities: (1) Activities of the facility manager side where the routine FM work is performed including the review of work orders, scheduling and assigning inspection and maintenance tasks using the IAV module; and (2) Activities of the field worker (e.g., inspector) who uses a tablet to perform the assigned tasks in an AR module and collaborate with the facility manager in real time. The *Task database* is where all the task-related data are stored, shared and retrieved when needed. CBIM3R-FMS requires using georeferenced BIM-based facility data, which is important for FM tasks collaboration using the AR module. In addition, the facility manager should know both the target element and the field worker locations to know how to assign and support tasks.

Based on the framework introduced in Chapter 3, this chapter discuses tracking and visualization methods which are: (1) Hybrid tracking method for AR module; (2) Multisource data modelling, integration and exchange for AR and IAV modules, including model customization method for the

AR module; (3) Automatic BIM-based lighting for AR and IAV model; and (4) Visualization methods for CBIM3R-FMS modules including virtual hatch for the AR module and multilayer view for the two modules.

4.2 TRACKING METHODS FOR CBIM3R-FMS

4.2.1 Hybrid tracking method for AR module

As discussed in Section 2.6.2, feature-based tracking has some limitations and it is important to maintain tracking accuracy for AR applications. In some cases, using feature-based tracking alone is not efficient. For example, because of the repetitive nature and patterned style of the multi-story office building design, unique features can be hard to find. This similarity in building elements design may reduce the efficiency of the feature-based tracking system since the *Tracking database* has similar features registered. In addition, the feature-based tracking requires the system to search in a large database that has a large number of registered tracking data.

To minimize the search scope and avoid similarity issues of the registered features, this research uses markers attached to the wall near the main door of each space in the facility. The marker is used to initiate tracking and limit the search for the registered feature-based tracking data. In addition, feature-based tracking requires continuously detecting clear features that are not disturbed by glare or light reflections. The gyroscope of the tablet can be used to compensate for the loss of feature-based tracking, assuming that the field worker at fixed position and he/she is only changing the orientation of the tablet. Figure 4-1 shows the flowchart of the method for the hybrid tracking mode activation.

First, the inspector enters the assigned inspection task space and scans the attached marker. The marker is registered in the makers' database and is linked with its relevant feature-based tracking data stored in the *Tracking database*. The tracking data are used to calculate the pose of the inspector. Once the pose is estimated, the scene is augmented with the relevant 3D objects. If the registered features are still detected, the inspector can proceed with the inspection task. If not, the sensor-based tracking is activated allowing the inspector to complete the inspection task. Once the feature-based tracking recognizes registered features again, the sensor-based tracking is deactivated to avoid the flickering of augmenting objects.

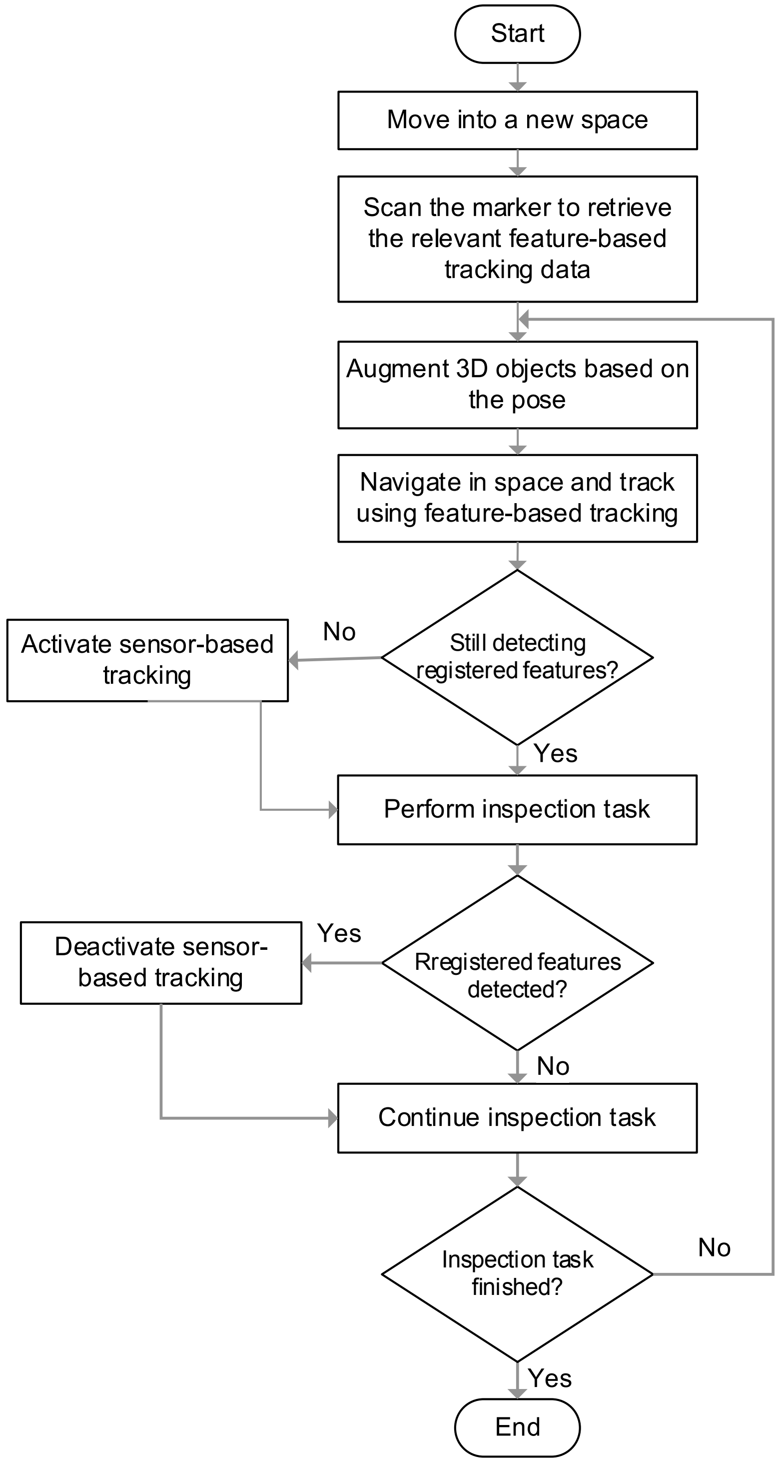


Figure 4-1 Hybrid tracking method

The accuracy of tracking is essential to align the video with the augmentation in the AR module. For the IAV module, aligning the virtual camera FOV used at the office-side with the physical camera FOV of the tablet that the field worker is using is more difficult because the accuracy of alignment depends on the AR tracking method, the stability of data streaming and the possible latency of rendering the results by the hardware.

4.2.2 Tracking methods for IAV module

In the IAV module, two types of tracking are used: (1) Tracking the head pose of the facility manager; and (2) Tracking his/her hands movement. The head pose is tracked by IR cameras, which read signals from the embedded sensors in the Head-Mounted Display (HMD). These sensors are micro-electrical-mechanical (MEMS) sensors. The HMD pose is captured based on two types of tracking: (1) positional tracking using optical IR cameras and (2) inertial rotational tracking using accelerometer, gyroscope, and magnetometer. The movement of the user controllers is also tracked using the same technique and used to update the virtual hands in the IAV module. Figure 4-2 illustrates the ranges for the tracking IR cameras placed on the table (highlighted in green). The controllers and HMD 6-DOF movement (i.e., 3-axis rotational tracking and 3-axis positional tracking) is tracked within these ranges.

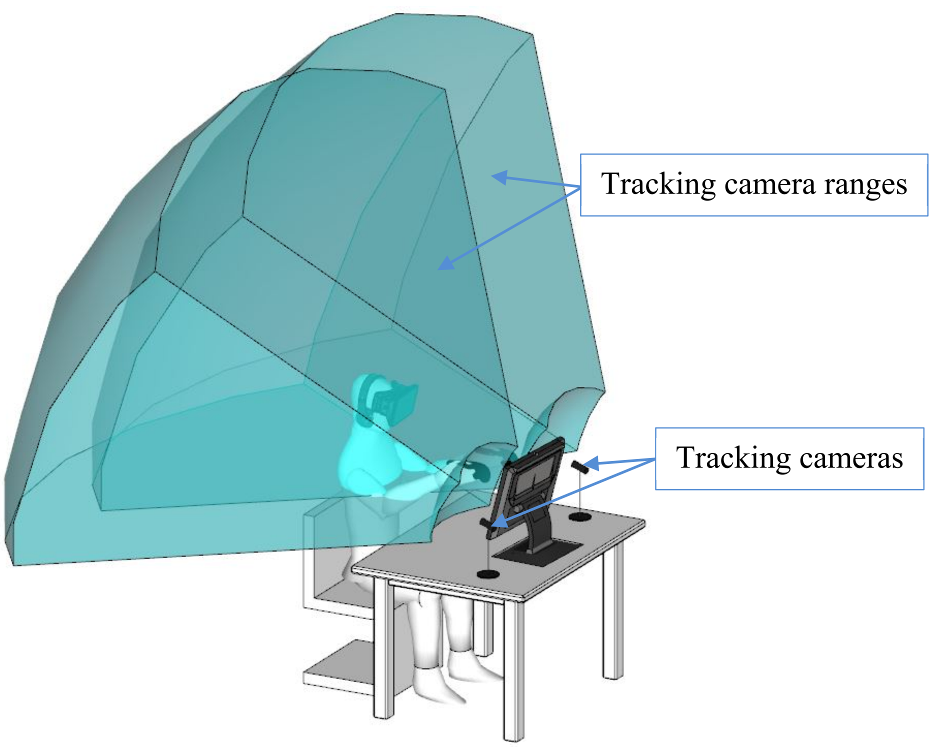


Figure 4-2 CBIM3R-FMS HMD FOV and tracking cameras ranges.

The virtual hands allow the facility manager to interact better in the VE by seeing where his/her hands are touching. During element picking or task tagging, specific button on the VR controller can be used for selecting elements, tagging tasks, marking and sketching when collaborating with the field work. The functionalities of the VR controllers' buttons are discussed in Section 6.2.2.

4.3 DATA INTEGRATION AND EXCHANGE FOR CBIM3R-FMS

This section discusses the main steps for constructing the BIM model using IFC-compatible BIM systems. The location represented by the global coordinates of each facility component is essential for FM operations. The BIM model used in FM contains geometric and non-geometric data. The geometric data of a building provide the graphical representation of the building model. This research uses XML-based data format to represent the building attribute data because it is easy to understand. Before interacting with the BIM model, it is important to correctly geo-reference the model to facilitate the collaboration between stakeholders. For example, the facility manager can search for nearby resources to assist the tracked field worker. This step can save time and improve productivity.

4.3.1 Data integration

To build large-scale VEs for CBIM3R-FMS that satisfy the requirements of FM tasks, data from different sources need to be integrated as shown in Figure 4-3. The integration process is based on three phases: (a) Data collection, (b) Data conversion, and (c) Data interaction.

(a) Data collection
The data collection phase requires good knowledge of BIM data formats, their LoDs, and BIM modeling tools. Besides BIM data formats, CityGML is a suitable data format for representing large-scale facilities (e.g., university campus) (CityGML 2018). This data format consists of georeferenced 3D geometrical data including façade textures, and comes with different LODs (LOD 0 for regional level to LOD 4 for interior architectural models). The LODs provided in CityGML allow users to identify spaces. Different LODs for BIM data (LOD300 for building exterior and LOD 500 for building interior) are prepared to satisfy the requirement of FM tasks.

Additional 3D models are prepared for interaction modalities that are explained in Section 5.4 and virtual hatch. Task information including task schedule and reported defects records are prepared.

As a parallel step, feature-based tracking data should be registered and stored in *Tracking database*, which can be used later in the interaction phase.

(b) Data conversion

The data conversion is necessary due to the limitation of the proposed development environment. Data collected are processed as geometric data containing 3D models and non-geometric data containing BIM attributes. As geometric models, 3D objects for the interaction modalities and virtual hatch models, as well as building exterior and interior models are georeferenced. The BIM-based geometric model should be processed to provide an AR-suitable optimized geometry that satisfies the AR rendering and interaction requirements. That is due to the fact that building elements, including walls, ceilings and floors do not have to be rendered since the AR user can see the real objects. As BIM attributes data, with high LOD model attributes, the XML-based attribute data are easy to parse, retrieve and share. Furthermore, the geometrical data conversion should be to a suitable format (FBX) to facilitate the real-time rendering in MR. Furthermore, process information including tasks scheduling, assigned tasks and resources are stored directly in *Task database*. Also, defects related data such as reported defects, their severity levels and reporting dates are stored in *Defect database.*

(c) Data interaction

The interaction phase consists of AR and IAV visualization and pose tracking components. The virtual contents of the VE are linked using unique identification numbers (IDs) from the optimized model with the IfcXML *BIM database*, which allows data retrieval for any specific building element information. The IfcXML, as an interoperability standard, is capable of exchanging data to/from engineering applications. Based on the retrieved ID, relevant data about assigned tasks or reported defects are retrieved from *Task* and *Defect databases*. *Task database* contains data of cost, activities' scheduling and other process information, such as maintenance and inspection activities

On the tracking components side, the location of the field worker is critical to define the area and objects of interest. The feature-based tracking data processed in phase (b) are stored in the *Tracking database*. In real-time operations, the tracking is done based on the hybrid tracking method, as explained in Section 4.2.1. The hierarchy structure in BIM allows the inspectors to link the defects to related components. It also allows field workers to retrieve and visualize building components based on the required task. For example, in the AR mode, a maintenance worker can see the drywall and the studs to find the available spaces to drill a hole for installing a pipe.

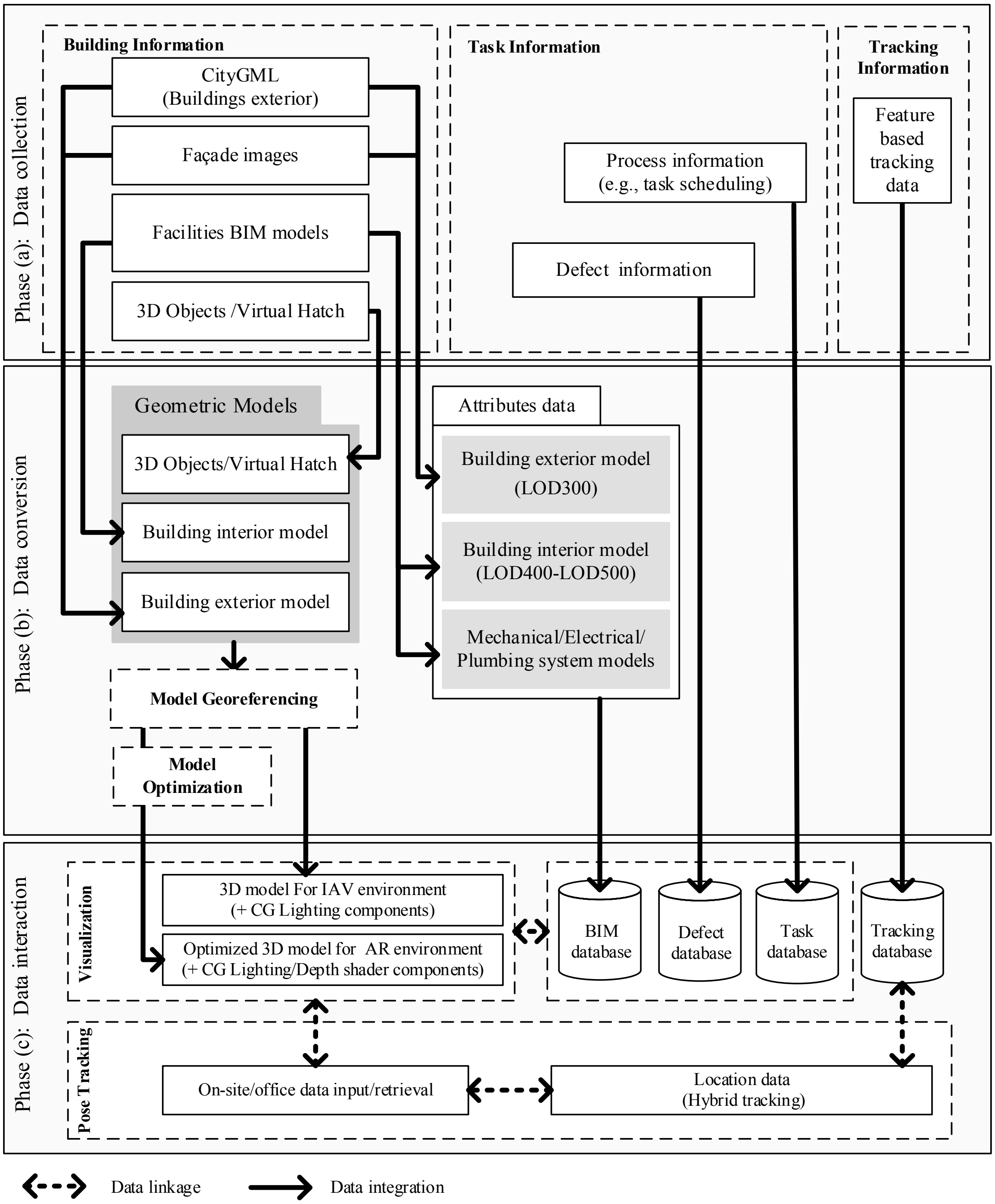


Figure 4-3 Multisource data integration

4.3.2 Automatic BIM-based lighting for AR and IAV modules

To accurately replicate the effect of the real-world lighting elements (e.g., spotlights lamps) in the AR and IAV environments, an automated process for capturing 3D lighting elements from the BIM model and their parameters (i.e., type, photometric values, location, and rotation) is developed. Based on the real lighting element parameters, a virtual light source can be created, positioned, and adjusted to mimic the original element's lighting effects. Figure 4-4 illustrates the main steps of this process. First, the BIM model is searched to find building elements that emit artificial or natural light, such as windows, spotlights, light bulbs, etc. For each element, the element is selected and its type, ID, and parameters are retrieved.

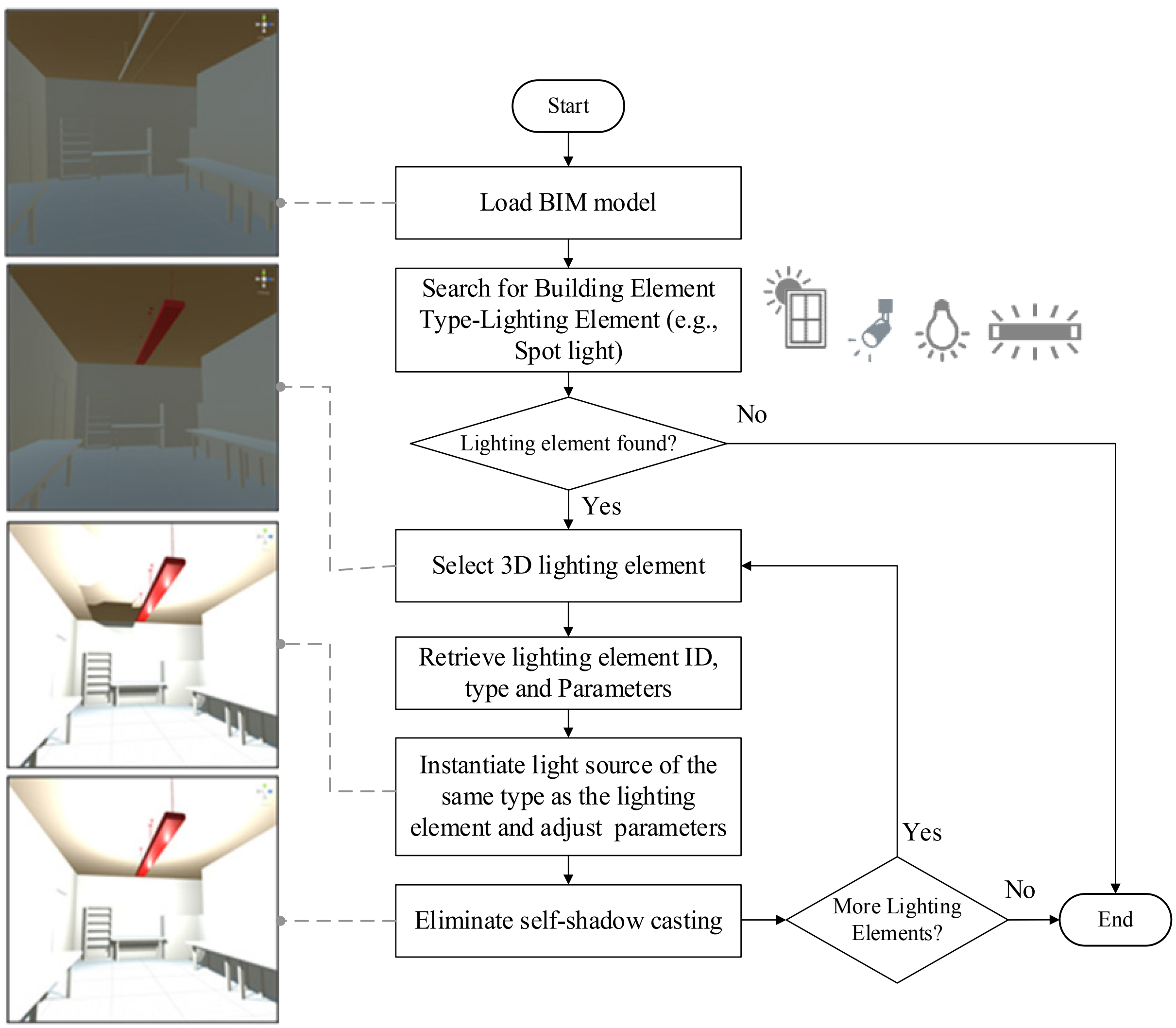


Figure 4-4 Automatic BIM-based lighting generation process

The parameters include the location, orientation, scale and photometric values (i.e., light intensity and color). Based on these parameters, equivalent light source is instantiated and positioned. Eliminating self-shadow is an additional step to prevent the lighting element from casting shadows.

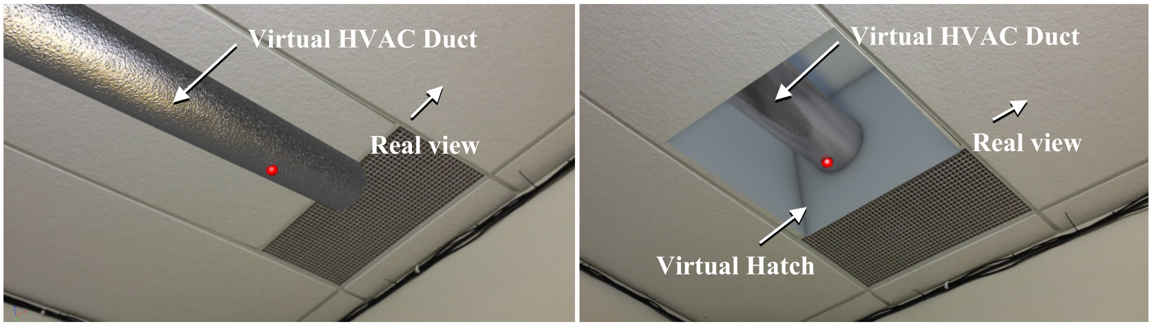
4.4 VISUALIZATION METHODS FOR CBIM3R-FMS

This research proposes two methods to enhance the visualization and the MR experiences for both the field worker and the office facility manager. These methods include the *Virtual Hatch (VH) and* the *Multi-Layer MR views*.

4.4.1 Virtual hatch for AR module

The visualization in AR focuses on superimposing virtual objects over the real view considering their geospatial relation. The visualization issues of not correctly representing the depth order of real and augmenting virtual objects cause misperception in AR because some virtual objects could be located behind some real objects that will occlude them. For example, when augmenting an HVAC duct hidden behind a false ceiling, the user cannot determine that the duct is behind the ceiling. Also, the scope of the part of the duct to be shown in the AR view is not geometrically defined, which means that the user may be confused about the part he/she should focus on. In practice, to inspect or maintain an HVAC duct, the field worker needs to take off the ceiling panels or cut open a part of the wall to allow him/her perform his/her task. The virtual hatch is designed as a virtual opening that limits the rendering of the hidden augmenting objects using a visual occlusion technique to give the illusion of an opening, which helps the user understand the MR environment.

In this research, an object occlusion rendering technique (Lee et al. 2003) is used to realize the virtual hatch. The occlusion is applied on one plane of the virtual hatch box model to occlude only the exterior part of the box model. The virtual hatch can be dragged on a building surface (e.g., a wall) using a gesture dragging function in two dimensions. Furthermore, using two-finger gesture manipulation allows the field worker to change the size of the virtual hatch to cover the area of interest. Figure 4-5 shows a comparison between simple AR view for HVAC duct (Figure 4-5(a)) and AR view, after applying the virtual hatch (Figure 4-5(b)).



(a) Simple AR view of HVAC duct (b) AR view after applying the virtual hatch

Figure 4-5 Comparison between AR views of HVAC duct before and after applying virtual hatch

The process includes the following steps: (1) Data preprocessing, (2) Real-time on-site processes. The data preprocessing consists of data collection, modeling and integration for FM data, video, BIM, and 3D hatch model. The rendering requirements are defined in the data preprocessing stage, which include model texturing, lighting, and occlusion requirements. Then, the rendering requirements with the modeled data are reproduced for real-time AR rendering of video and 3D contents. The rendered 3D contents are superimposed in the AR module where video is used as a background. The optimized 3D model is used as a static 3D model representing the building component (e.g. HVAC duct), and the occluded 3D model is used as a dynamic 3D model representing the virtual hatch. The AR module is supported with interaction methods including: (a) object picking for assigning defects markers or selecting a facility component; (b) object dragging for controlling the virtual hatch size and position. Several issues have been noticed regarding real-virtual worlds mismatching including the static and the dynamic objects registrations for the HVAC duct and the virtual hatch model, respectively, the resolution differences between the real view and the rendered objects, virtual hatch scale, contrast, depth, and vertical alignment. Therefore, readjusting these setting may result in a better matching for the two worlds. Figure 4-6 illustrates the spatial relation between the field worker, the false ceiling, the HVAC duct and the virtual hatch box.

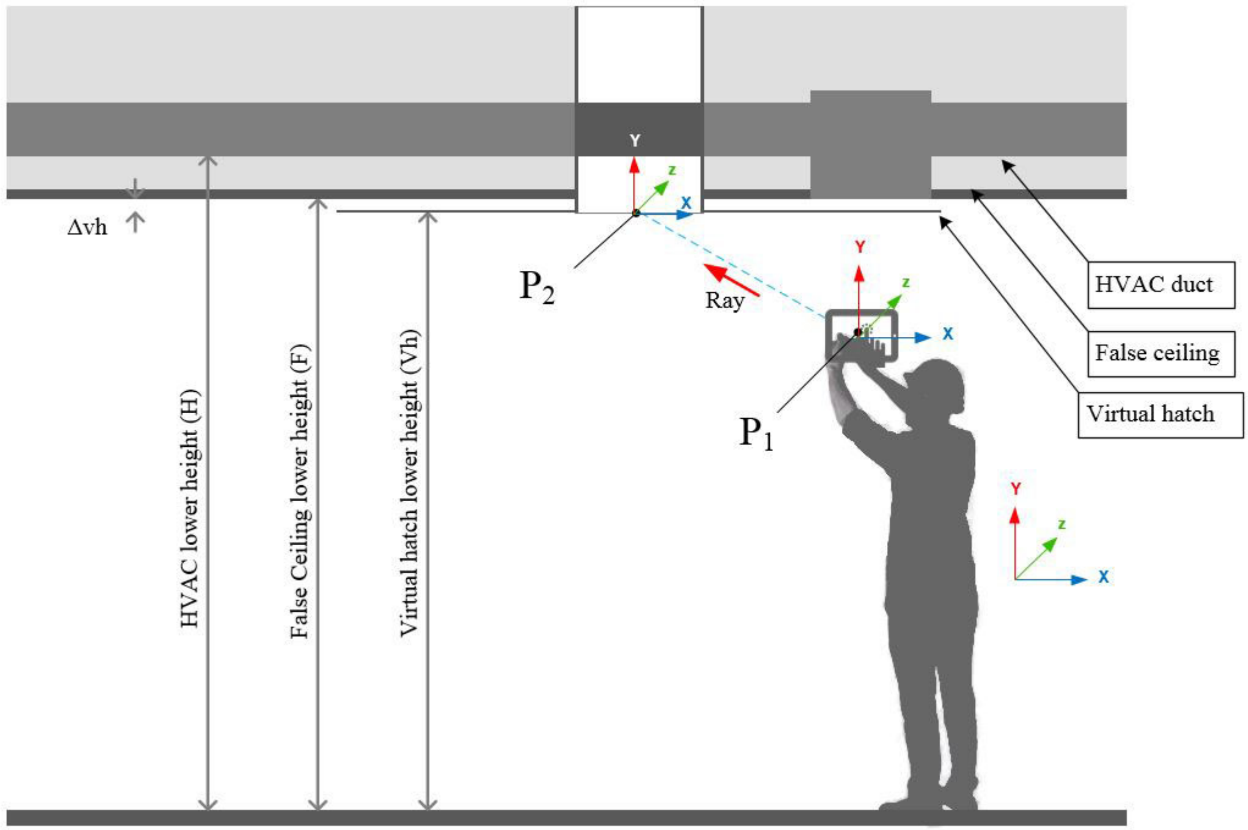


Figure 4-6 Virtual hatch concept layout

The distance (Δvh) represents the offset required to avoid objects overlapping. This distance depends on the accuracy of tracking. When the hybrid tracking provides stable augmentation of both the HVAC duct and the virtual hatch, Δvh can be few centimeters. However, if the augmenting objects are not stable, Δvh should be a larger number. The HVAC lower height (H) and false ceiling lower height (F) can be retrieved from the BIM attributes. The virtual hatch lower height (Vh) is calculated based on the difference between F and Δvh.

$$Vh = F - \Delta\text{vh} \qquad \text{Equation 4-1}$$

Figure 4-7 illustrates the process of updating the virtual hatch position information based on the user interaction. When the field worker starts navigating in the space aiming the tablet towards his/her point of interest (e.g., investigating a cause of water leakage on a wall), a virtual ray is instantiated to detect a building element (e.g., false ceiling). This element is covering other building elements (e.g., HVAC ducts, wiring, pipes). After detecting the element, the hit point (P_1) is calculated and used to position the virtual hatch box. When the field worker drags the virtual hatch to his area of interest to investigate what is behind the false ceiling, the new position of the virtual hatch is updated using only the X and Y coordinates of the tablet screen dragging point and maintain the same Z coordinate captured by the initial raycasting method. Each time the field worker rotates the tablet at any direction, the ray cast method update the virtual hatch position.

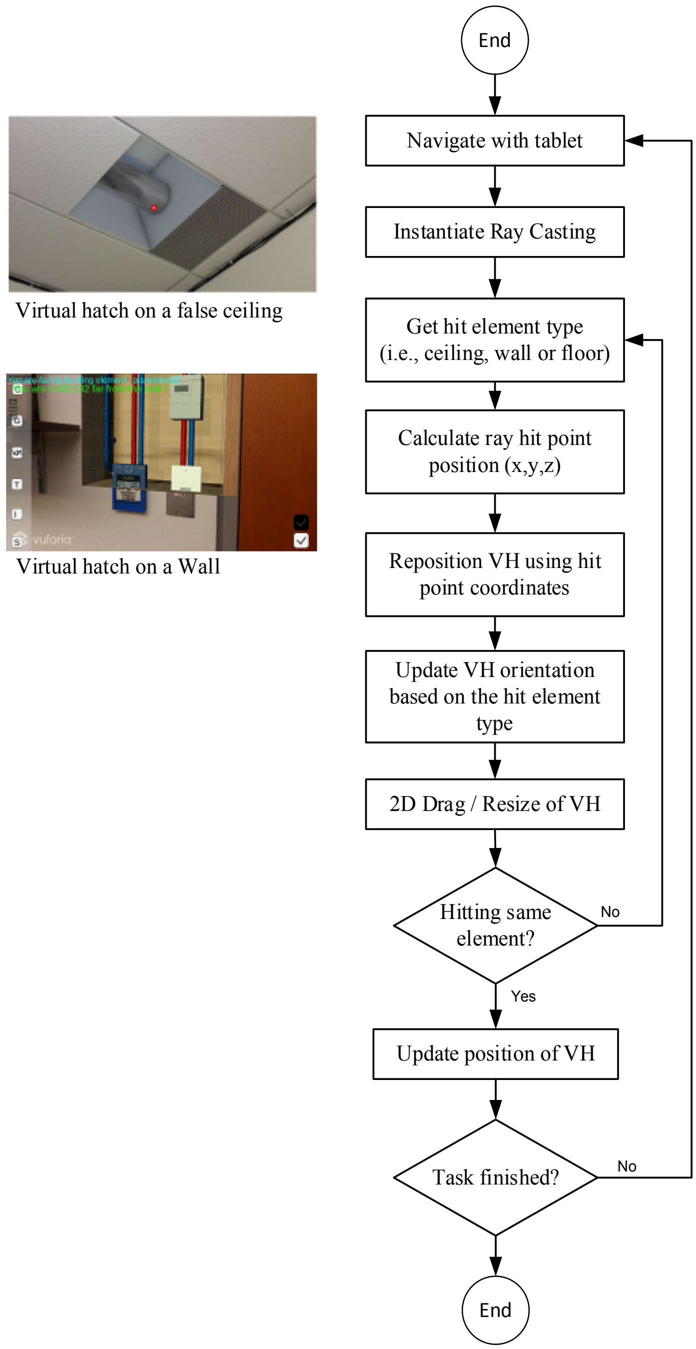


Figure 4-7 Process of positioning and orienting the Virtual Hatch

As shown in Figure 4-8, direct manipulation of the virtual hatch is set into four events: (1) Selection by using one finger, (2) Movement by moving the finger around, (3) Rotating by using two fingers at the same time while rotating one around the other, (4) Scaling by minimizing or maximizing the distance between the two fingers.

Figure 4-8 Direct manipulation actions of the virtual hatch

4.4.2 Multi-layer MR scene views

Figure 4-9 shows two sides of the proposed system. Each side's main view has several layers of information. On the field worker side, the main AR scene has the following layers: (1) tablet camera view, (2) georeferenced BIM model, (3) sensory data, (4) BIM-based non-geometric textual information, (5) input GUI, and (6) remote collaboration modalities. The order of these layers is important to not confuse the field worker.

There are sensors such as ultrasonic detectors, microwave imaging, and laser scanners that can assist in providing additional information about space and components conditions, especially when these components are georeferenced. This research investigates only one type of sensory data. In this research, the sensory data is coming from mobile applications (e.g., thermal imaging), are mapped correctly with AR module FOV. At the facility manager side, a streamed video from the field worker will be used as a scaled window on layer B augmented on the virtual scene as an IAV environment. The sensory data (i.e., thermal images) on layer 3 in the AR scene can be steamed and used the scaled window on layer C. The window position is updated based on the steamed pose data of the tablet camera of the AR module. The facility manager needs an input GUI located as layer D. The guiding arrow object is in layer E, which can be streamed to the AR module as layer 1. For visual interaction, layer E of the IVC module is used to visualize (e.g. a guiding arrow) controlled by the field worker; while layer 6 of the AR module is used to visualize the interaction (e.g. another guiding arrow with different color) controlled by the facility manager.

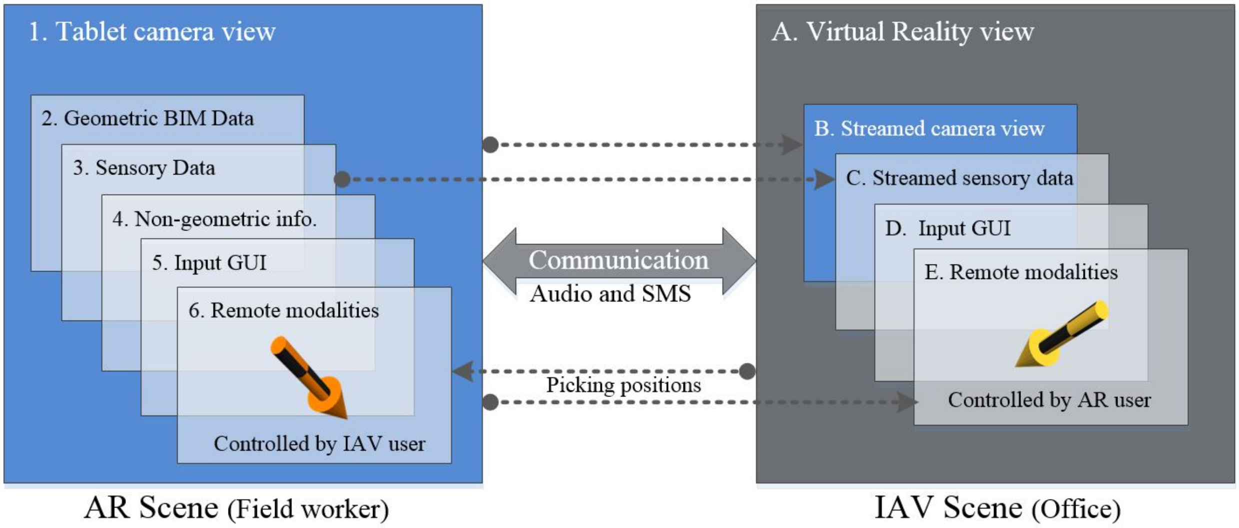


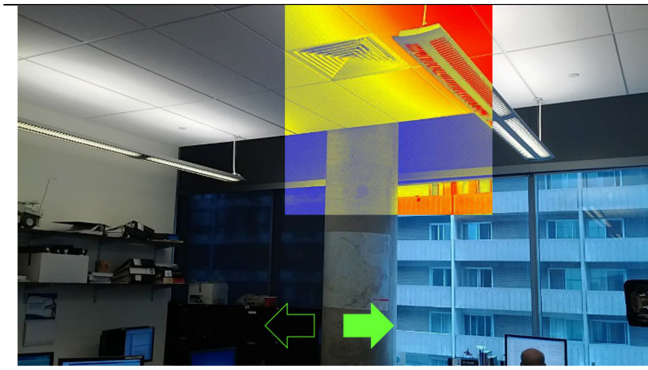
Figure 4-9 Multi-layer MR views

Defining and visualizing defects in CBIM3R-FMS is an important issue. Therefore, generic 3D color-coded symbols are used to represent defects in both IVA and AR modules of the system. There are several issues that need to be considered to enhance the MR experience to allow the users to perform tasks efficiently. For example, a 3D red sphere can represent a defect type of crack with high severity. However, this red sphere cannot be noticed when located on a red-color wall. Therefore, applying visual effects by changing colors or applying animation can help the users see the defects within the AR and IAV environments. The multilayer allows users to choose what to show on their view as a single layer or multiple layers for comparison purposes. Table 4-1 shows multiple screen shots of the multilayer view, augmenting multisource contents during IVC session. It shows the thermal image using the sensory data layer (layer 3), element information using non-geometric information layer (layer 4), and the remote sketch (layer 6).

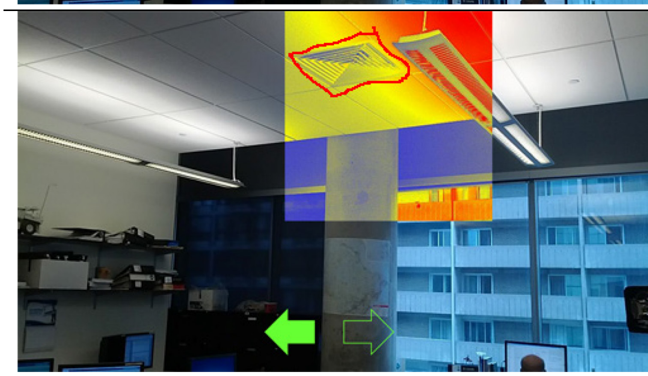
Table 4-1 Multi-layer inspector view

<table>
<tr><th>Screenshot</th><th>Description</th></tr>
<tr><td></td><td>

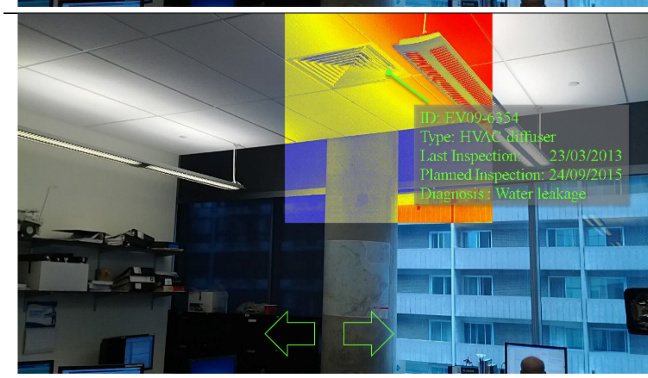
- Camera view with 2D guiding arrows at the bottom.
- Green arrows indicate that the facility manager is ready to communicate using IVC.

</td></tr>
<tr><td></td><td>

- Thermal image superimposed on the camera view.
- The right green arrow indicate that the facility manager is looking at the right side.

</td></tr>
<tr><td></td><td>

- The left green arrow indicate that the facility manager is looking at the left side focusing on the AC diffuser.
- The facility manager is remotely marking the defect area by a red sketch.

</td></tr>
<tr><td>
</td><td>

- Inspector picks on the AC diffuser to check its historical inspection data (augmented as green text).

</td></tr>
</table>

4.5 SUMMARY

The hybrid tracking method is discussed in this chapter. This method is based on the integration of two CV-based tracking methods including marker-based and feature-based tracking, and sensor-based using the gyroscope rotation data. Also, this chapter presents data modeling, integration and exchange methods to satisfy the requirement of IVC between facility field workers and the manager at the office. An innovative and practical method is discussed for multisource large-scale facilities' data modeling and integration for MR. This method is based on synthesizing information from CityGML, BIM, and databases of the defects, tasks, and tracking. Furthermore, the creation of these georeferenced models with different LODs is presented for both building exterior and building interior. Two methods of the automated modeling processes are presented: (1) automatic BIM model optimization and customization for the AR module, and (2) automatic BIM-based lighting for AR and IAV modules.

The third major part of this chapter discusses two visualization methods for improving the AR module users' visual perception. The virtual hatch is discussed in Section 4.4.1. The virtual hatch can improve the field worker depth perception, which allows him/her to perform FM field tasks naturally without visual disturbance. The multi-layer MR view is a visualization concept discussed in Section 4.4.2. Improving visualization is an important step to allow the field worker using the AR module and the facility manager using the IAV module to interact with each other and with their enhanced views. The implementation and validation of the proposed methods are discussed in Chapters 6 and 7, respectively.

CHAPTER 5 MR-BASED INTERACTIVE VISUAL COLLABORATION

5.1 INTRODUCTION

In FM, there are many stakeholders involved in the inspection and maintenance processes. As indicated in Chapter 3, this research focuses on two main stakeholders who are the facility manager and the field worker. The manager is usually at the office and his/her main responsibilities are reviewing reports and making decisions, assigning work orders, and managing resources (i.e., budget, workers, and materials). The field worker can be either an inspector or a maintenance worker. The main responsibilities of the inspector are reporting defects based on routine inspection or requested inspection by the facility users. The main responsibility of the maintenance worker is performing scheduled maintenance tasks. CBIM3R-FMS allows these stakeholders to communicate effectively through MR-based interfaces.

The main objective of this chapter is to discuss an interaction method between the field worker and the facility manager at the office in an interactive visual collaboration mode. Based on the frame work introduced in Section 3.4, the communication between the field worker and the remote office requires special settings and data preparation. These settings require using different visualization technologies and different hardware for each module.

This chapter discusses an innovative method for IVC between the facility manager and the field worker using different MR methods. First, a discussion about what is MR-based collaboration is presented in Section 5.2. Second, the roles of the office-side IAV and the field-side AR modules in the interaction are discussed in Sections 5.2.1 and 5.2.2, respectively. Third, the interaction processes are discussed in Section 5.3 and the interaction modalities for AR and IAV modules are discussed in Section 5.4. Finally, a summary of this chapter is discussed in Section 5.5.

5.2 INTERACTIVE VISUAL COLLABORATION

The IVC has two modes: (1) non-constrained mode where the field worker and facility manage FOVs are not matched and synchronized, and (2) constrained mode where their FOVs are synchronized. The IVC between the facility manager at the office and the field worker is important to avoid misinterpretation of the assigned inspection or maintenance tasks. This can lead to unnecessary rework, which consequently reduces productivity as discussed in Section 3.2. In the MR-based collaboration, the manager at the office can assign location-based tasks and instantly share this information with the field worker using the IAV module. On the other side, the field worker, using the mobile AR module, can share the real view he/she sees with the manager. Visual guidance is given by the manager to facilitate performing tasks. As shown in Figure 5-1, the proposed system has two sides that support interaction and collaboration.

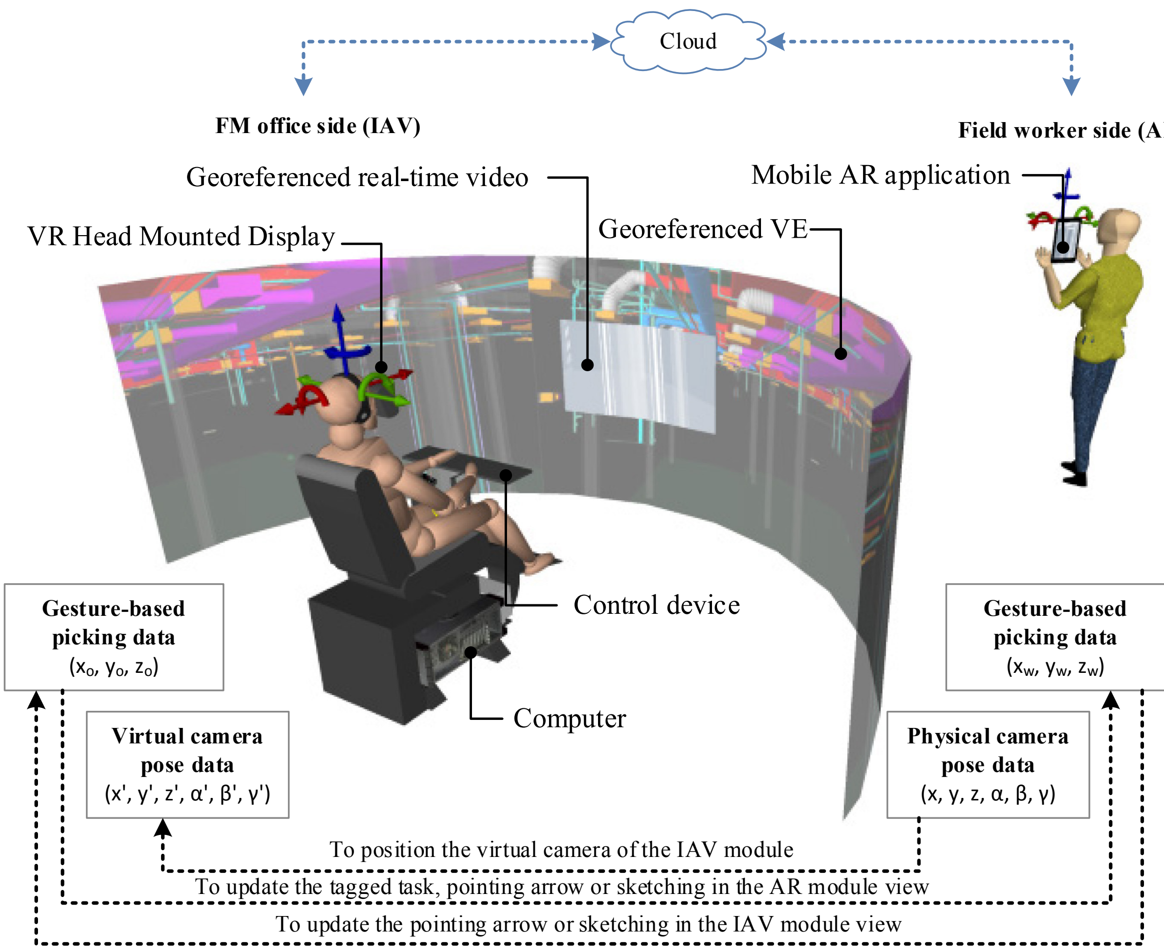


Figure 5-1 Interactive visual collaboration

5.2.1 IAV-based module

On the office IAV side, the manager points at the specific place or component where the inspection or the maintenance should take place. The location of this picking is captured using ray tracing method. This location information is used to place the generated task tag in the VE. The location information along with a brief task description and the target building element information are streamed to the on-site mobile AR-based module.

5.2.2 Mobile AR-based module

Using the mobile AR-based module, the field worker views the marked tasks and navigates through the real environment with the help of a rendered direction arrow for visual guidance. The arrow orientation is calculated based on the tagged task position and the tablet camera position. When the field worker reaches the assigned place and finds the task tag in the AR view, he/she marks the defect on the element through the AR interface. After marking the defect, the image of the defected element and the location information of the defect mark (e.g. a red sphere representing leakage on the ceiling) are streamed and placed in the VE.

In this two-way interaction, the manager is immersed in the VE to have more access to the facility information and to support the FM tasks by IVC and data sharing with the field worker. The collaboration aspect of the proposed framework allows both the manager at the office and the field worker, not only to share the geometrical data of what they are interested in, but also to share their point of view as the pose of the virtual camera in the office-side IAV can be changed based on the pose of the field worker camera in the constrained mode.

During an IVC session, two sets of pose data are streamed from each module: (1) camera pose data (i.e., location and orientation), and (2) picking point data (location of the defect). First, to accurately position the manager in the IAV environment, the global coordinates and the orientation of the field worker ($x, y, z, \alpha, \beta, \gamma$) should be streamed and converted to the IAV coordinate system ($x', y', z', \alpha', \beta', \gamma'$). This pose data sharing allows the manager to compare the real view of the target building element, which the inspector is looking at through the tablet, with the relevant element in the IVE environment. On the other hand, the three degrees of freedom (DoFs) of the head movement of the manager in the IAV environment can be used to update 2D guiding arrows in the AR module to show the manager's point of interest. In addition, audio-based and text-based chatting can support the communication experience by sharing verbal descriptions or comments. Second, when the facility manager starts the IVC session with the field worker, his/her gesture-based picking location values (x_o, y_o, z_o), which are used to instantiate task marks, pointing arrows, or sketches, are streamed to the AR module in real time. Then, these values are used to replicate the visual modalities (i.e., task marks, pointing arrow, or sketch). On the other hand, when the field worker adds annotation (e.g., a sketch), his/her gesture-based picking location values (x_w, y_w, z_w) are streamed to the IAV module. These values are used to replicate his sketch in the IAV module.

5.3 MR-BASED INSPECTION PROCESS SEQUENCE DIAGRAM

The IVC depends on the real-time communication between the facility manager and the field worker, as well as their sequenced interactions with the databases. Figure 5-2 shows the sequence diagram of data communication between the two actors: the facility manger (FM_IAV) and the felid worker (Inspector_AR). The actors connect with the databases for: tasks (Task_DB), defects (Defect_DB), BIM information (BIM_DB), and tracking data (Tracking_DB). The communication follows the steps below.

Steps 1& 2: The features surrounding the location of the Inspector_AR actor are detected. The preprocessed feature-based Tracking Data (TD) are loaded from the Tracking_DB.

Step 3: After estimating the pose, Inspector_AR sends his/her 6-DOF pose information including location (x, y, z) and orientation (α, β, γ) to FM_IAV.

Steps 4&5: Based on the received pose information, the virtual camera pose is updated in the IAV module and the FM_IAV view is updated. These steps are only used when the IVC starts (i.e. in the constrained mode).

Steps 6&7: The Inspector_AR reports the defect to the Defect_DB indicating the type and severity of the defect. An automated confirmation with a ticket number is sent back to Inspector_AR.

Steps 8&9: The FM_IAV retrieves defects from the Defect_DB. The FM_IAV updates the Defect_DB after reviewing and making a decision about re-scheduling or initiating a work order.

Steps 10&11: The FM_IAV reviews the schedule from the Task_DB. The FM_IAV assigns a task as a geotagged task and the task information is sent to Task_DB.

Steps 12&13: The FM_IAV updates his/her view with the attribute data retrieved from the BIM_DB. Using the marking method in the IAV, the FM_IAV assigns a task in the VE, and the marked space ID and the central point coordinates of the bounding box are sent to the BIM_DB.

Steps 14&15: The Inspector_AR retrieves the assigned geotagged task from Task_DB and the task's relative BIM information from the BIM_DB.

Steps 16&17: The Inspector_AR sends inspected defect data to the Defect_DB. The Inspector_AR updates his/her scene with any historical data stored in the Defect_DB related to the defect.

Step 18: Once the inspection is done, the Inspector_AR updates Task_DB.

Steps 19&20: During inspection, Inspector_AR may send support request to the FM_IAV. The FM_IAV updates the Inspector_AR with pose information for the guidance arrow movement.

Steps 21&22: The FM_IAV sends instructions as a textual or an audio massage to the Inspector_AR. The Inspector_AR responds with a feedback message. The steps from 19 to 22 are in a continuous loop, conditioned on whether the IVC is active or not.

Steps 23&24: The FM_IAV reviews the defect information from the Defect_DB and updates the Defect_DB if any extra information is needed.

Steps 25&26: The FM_IAV reviews the Task_DB to check if extra work or information is needed and updates the Task_DB if needed.

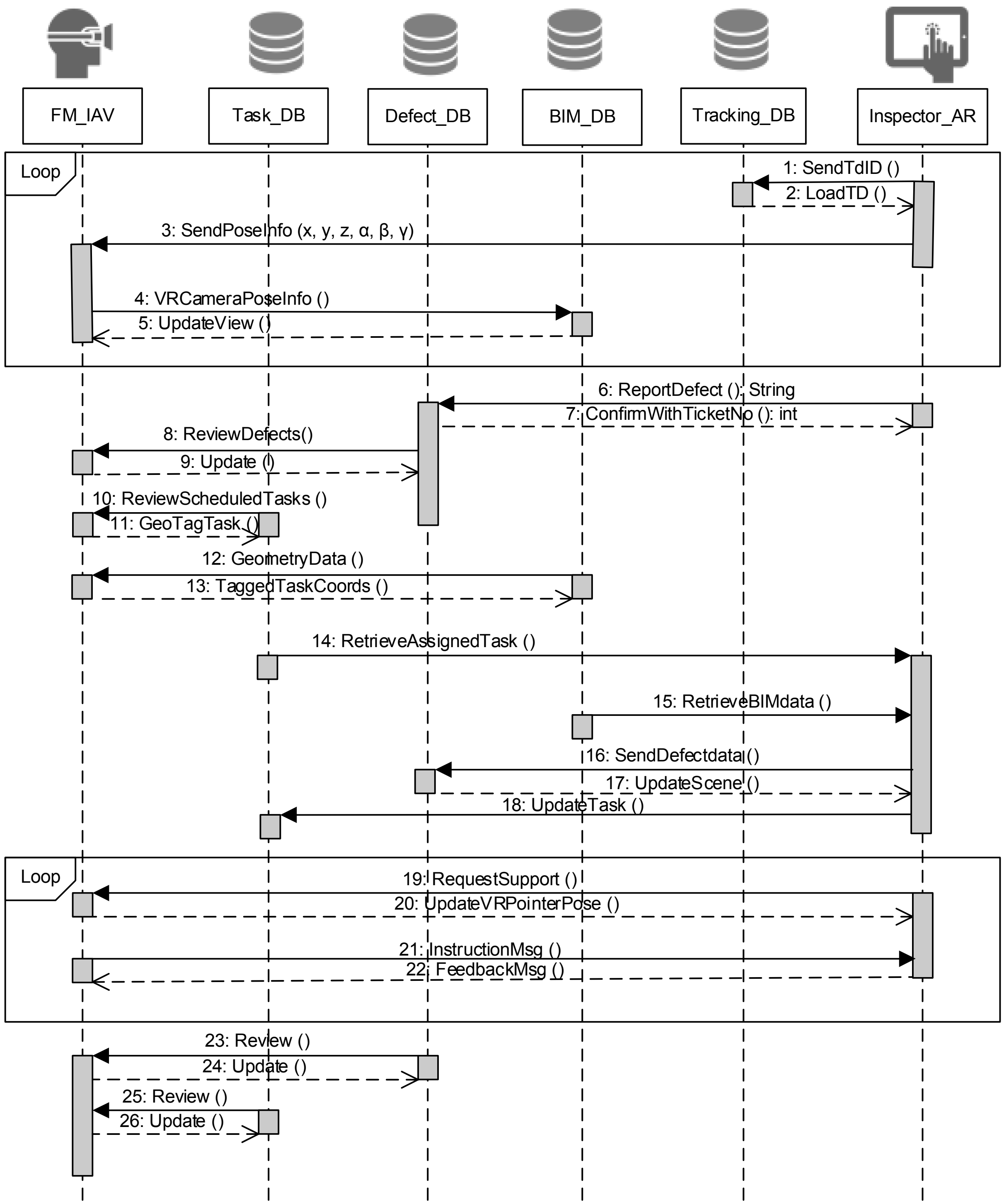


Figure 5-2 Sequence diagram of data communication between AR and IAV modules

5.4 INTERACTION MODALITIES FOR AR AND IAV MODULES

Picking (Han 2018) is the main technique used for interacting with the VE in the AR and IAV modules. The pick object can be a ray, which is extended from the finger picking position through the VE. When a pick is requested, pickable objects that intersect with the pick object are computed. The pick returns a list of objects, from which the nearest object can be computed. Figure 5-3 shows an example of the picking behavior used for marking a defect on a ceiling.

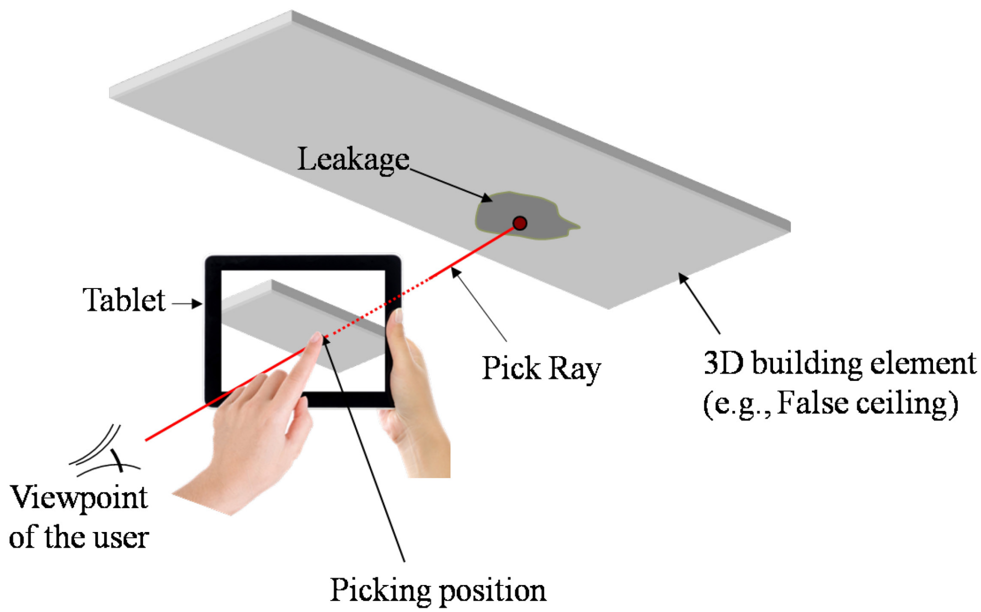


Figure 5-3 Example of picking using tablet-based AR

Picking can be used by the field worker or the facility manager for different purposes. The picking done by the facility manager is used to select an element, assign tasks, place pointing arrow or sketch in the IAV module. The picking done by the field worker allows him/her to select an element, mark defects, place pointing arrow or sketching in the AR module. In the case of marking defects, the intersection between the ray and the 3D object is used as the center point of the defect mark (e.g., a sphere). Figure 5-4 shows the different uses of the picking technique with different modalities for the AR and the IAV modules. Each module has two layers to deal with these modalities (i.e., created objects and received objects). Each user is manipulating different MR modalities: (1) The facility manager tags a task using a blue cube to represent a task place in the IAV module; (2) The same cube is instantiated and positioned in the AR module and 2D guiding arrows are used to refer to any off-screen objects to help the field worker find them in the AR module; (3) Color-coded georeferenced markers (e.g., sphere) are added by the field worker to represent defect severity. For example, a sever defect is tagged with a red animated marker, while a mild defect is tagged with a yellow static mark. Since the mark is georeferenced, the facility manager has the ability to search based on the location and components in the virtual environment to investigate possible causes; (4) The same objects will be visualized in both the AR and the IAV module and 2D guiding arrows are used to refer to any off-screen objects' positions to help the facility manager find them in the IAV module; (5) Pointing orange 3D arrows and green-line sketching are used by the field worker to refer to a specific area of interest in the real environment; (6) The same pointing arrows and sketches are shown in real time in the IAV module. Steps (7) and (8) are the same as steps (5) and (6) except with yellow color for the pointing arrow and red color for the sketching. It is important to use different colors to identify the user who made them. The right side of the figure shows the output of these IVC components in the two modules. Furthermore, the interaction with the 3D model is facilitated by selecting an element of the 3D building model using finger pointing on the tablet. This allows the inspector to interact with the VE by picking an element. The picking technique allows data retrieving for the selected element, and instantaneously displaying these data using AR.

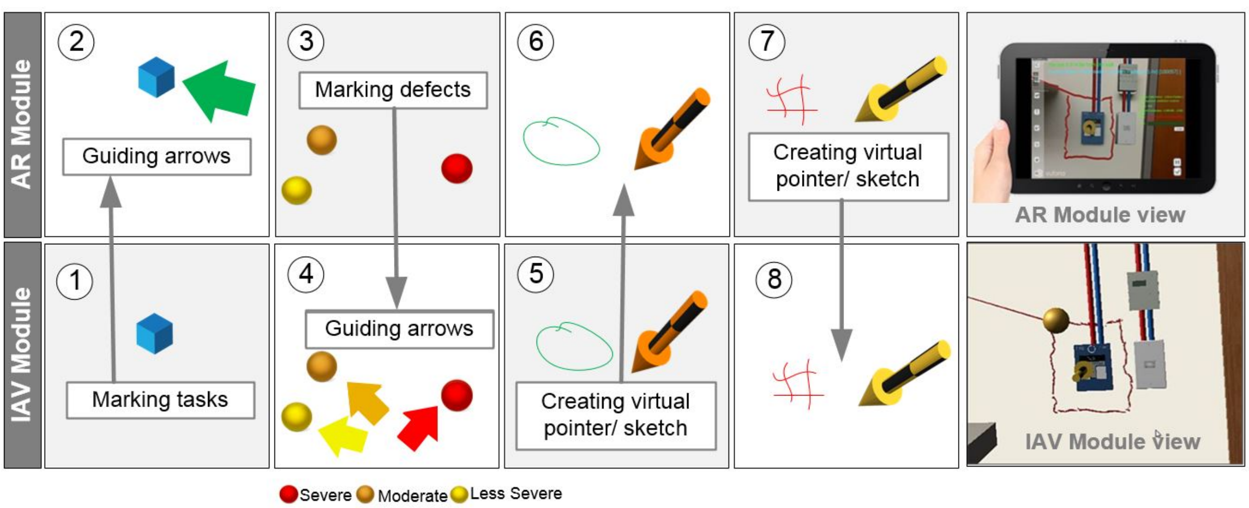


Figure 5-4 The uses of picking technique in AR and IAV modules.

In addition, inspection data can be added to the element inspection attributes and stored in the model database. Information about defect location, inspection date, etc., is automatically added by the system. This eliminates the need for extra effort and time to draw and write notes about defects information, which consequently minimizes cost and improves productivity.

5.5 SUMMARY

This chapter discusses the IVC method introduced in Chapter 3 between the AR and IAV modules. Collaboration and interaction methods for CBIM3R-FMS are based on the georeferenced VE discussed in Chapter 4. The IVC relies on integrating emerging technologies including HMDs and gesture-based tracking devices to improve interactions in the IAV environment. Unlike collaboration based on only data sharing, IVC allows the field worker to share his/her AR view with the remote facility manager, and at the same time, he/she receives the visual instructions remotely. The continuous interaction between the facility manager and the field worker is important for situation awareness. Improving the situation awareness requires reliable communication infrastructure and hardware as discussed in Section 6.2.2.

This telepresence MR experience allows exchanging important information to improve task performance. The inspection processes re-engineering discussed in Section 3.2 is the base of the IVC, and the sequence diagram of the interaction between the AR and IAV modules with the databases is discussed in Section 5.3. To realize the visualization part of the IVC mode, interaction modalities for the AR and IAV modules are presented in Section 5.4. The different shapes and colors of these modalities, as well as their locations in the multi-layer view, help the AR or IAV module users interact with each other. The IVC, as a core part of CBIM3R-FM, is fully implemented and discussed in Section 6.4.4 and validated by the usability testing discussed in Section 7.2.

The IVC presented in this chapter allows remote visual interaction for FM tasks. Being able to discuss tasks issues in real time with a remote expert or a decision maker is a valuable method to avoid confusion and task delays.

CHAPTER 6 IMPLEMENTATION AND CASE STUDY

6.1 INTRODUCTION

This chapter discusses the implementation of the proposed methods presented in Chapters 3, 4, and 5 and explains the step-by-step model integration and software development. Based on the system architecture discussed in Chapter 3, the implementation has three phases. First, developing the multisource BIM-based contents, which requires using several BIM tools for modeling the large-scale facilities, and then combining them in a game engine after applying the necessary georeferencing and coordinate transformations. Then, this geometric information is linked with the database. The second part of the implementation is the hybrid tracking method, which includes marker-based tracking, feature-based tracking as the main tracking method and sensor-based tracking using the tablet's gyroscope. Third, the prototype system is an application with two modules used by two types of users: the facility manager and the field worker. These two modules are fully implemented and tested. The development of the prototype system is presented briefly in this chapter. The complexity of the integration of different tools led us to use a game engine as the system authoring and development environment. To investigate the usability of the system, a case study is developed for an indoor inspection task. The model is based on multiple LODs to satisfy the requirements for the planned inspection testing scenario.

6.2 CBIM3R-FMS SOFTWARE AND HARDWARE REQUIREMENT

6.2.1 Software requirements

(1) Unity3D is a 3D visualization and game development system. The engine has many features including physics and rendering to allow creating interactive 3D VEs. The main reasons of choosing Unity3D for implementing the proposed framework are: (1) The game engine can be used as an authoring tool and it allows focusing on the concepts of the prototyping; (2) It has integration capabilities for developing AR and VR tools, linking with external databases and interoperability support (e.g., FBX's Autodesk native format); and (3) It has support of multiuser real-time collaboration and data sharing.

(2) Vuforia (Vuforia SDK 2018) is an AR Software Development Kit (SDK) for mobile devices that supports feature-based tracking. The main use of this tool in this research is to create the tracking data and use them within Unity3D development environment through Vuforia Unity3D plug-in. The plug-in is used to access the registered tracking data inside Unity3D and compare them with the detected features captured by the tablet camera.

(3) For BIM attribute database interaction, the IfcXML parser package uses Xerces Java Parser (Apache 2018). Xerces Java Parser provides XML parsing and generation, and implements the W3C XML and DOM (Document Object Model) standards, as well as SAX (Simple API for XML) standard. The parser is used to read IFC-based data of the building attributes and save them in the database.

(4) The hotspot application (i.e., Connectify) is installed on the server side PC where the IAV module is installed. This allows WLAN-based peer-to-peer connectivity between the two modules and connects them with the databases, as well as allows them to stream pose and video data and to call functions on the remote server.

6.2.2 Hardware requirements

The visualization of the MR contents as well as the local and remote interactivity of CBIM3R-FMS modules depend on specific hardware requirements. Figure 6-1 shows the used hardware in CBIM3R-FMS modules which are explained in the following:

(1) The AR module is implemented as feature-based mobile AR application installed on an Android tablet (Samsung Galaxy Tab S2 with 1.8GHz+1.4GHz Octa Core Processer and 3 GB RAM). The CMOS 8.0 MP back camera of the tablet is used for tracking and feeding the IAV module with video frames. The tablet has connectivity options including Wi-Fi, GPS and Bluetooth. Sensors on the tablet include a proximity sensor, accelerometer, ambient light sensor and gyroscope. However, in this research only the gyroscope is used for the hybrid tracking method as explained in Section 4.2.1. FLIR ONE camera (FlirOne 2018) is a thermal camera that can be attached to the tablet to provide thermal images. The camera has resolution of 160×120 pixels and the sensed temperature range is from -4°F to 248°F (-20° to 120°C). The camera sensitivity allows detecting temperature differences as small as 0.18° F (0.1° C).

The light weight of the camera (78 grams) makes it ideal for mobile applications. Figure 6-2(a) shows the thermal camera attached to the tablet and Figure 6-2(b) shows the thermal images in the AR module.

(2) The IAV module is implemented as a standalone application and runs on a desktop PC (Dell Precision T1700 with Intel(R) Core(TM)i7-4790 that has CPU processing speed of 3.60 GHz and 8 GB RAM). In addition, the IAV module uses three VR-based gadgets: (1) Oculus Rift for IAV visualization; (2) Touch controllers for gesture-based tracking; and (3) FLIR ONE for thermal imaging in the AR module. Oculus Rift (Oculus 2018) is a HMD with two touch controllers, which allow the facility manger to interact with the VE in the IAV module by tracking the head movement. The main reasons for selecting Oculus Rift for this application are its wide horizontal FOV (100°), display resolution (960×1080 pixels per eye), low-latency positional tracking, and the support of its SDK2 version for integrating with Unity3D game engine. The touch controllers allow simulating the movement of hands, so the facility manager can interact with virtual objects in a similar way to what he/she does in the real world.

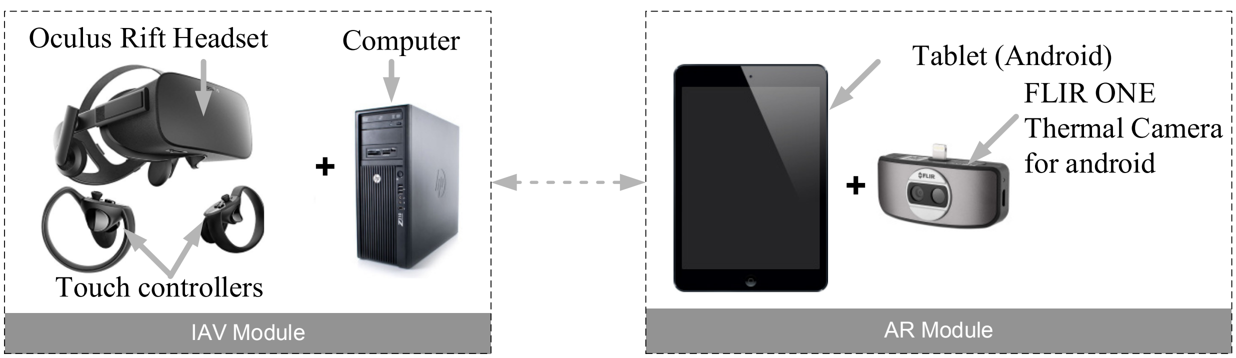
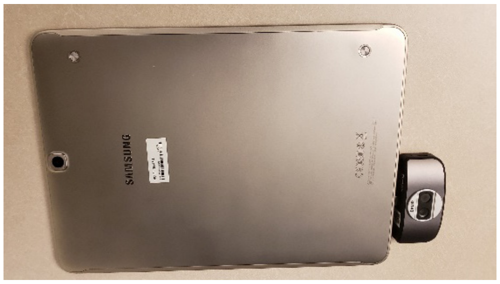


Figure 6-1 Hardware used in implementation



(a) Thermal camera attached to the tablet

(b) Capturing thermal images in AR module.

Figure 6-2 FLIR ONE thermal imaging camera

Figure 6-3 illustrates the IAV hardware components and the setting. Figure 6-4 shows the assigned functionalities for the two Oculus Rift touch controllers used for interaction in the IAV module.

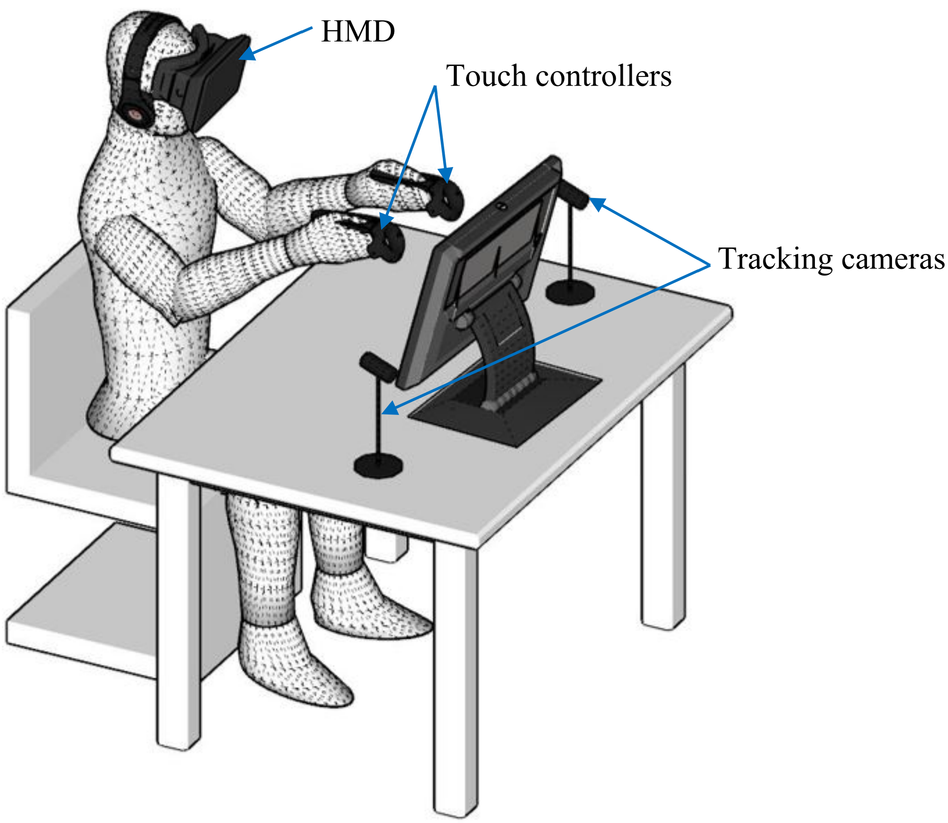


Figure 6-3 IAV module hardware components

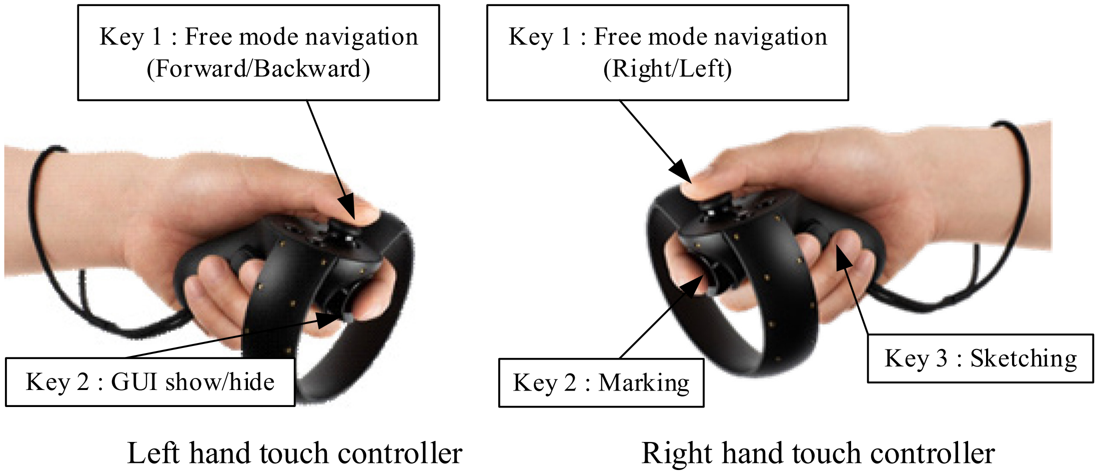


Figure 6-4 Interaction controllers functionalities in IAV module

6.3 MULTISOURCE DATA PROCESSING

The system architecture of CBIM3R-FMS has three parts: (1) the facility manager IAV module; (2) the field worker AR module; and (3) The server databases, which can be hosted at the office or in the cloud. To facilitate the development process, the prototype system was developed using Unity3D game engine (Unity3D 2018). The engine is used to build the VE and to allow the users to interact with the facility components in both modules, and then to collaborate by exchanging visual information about the assigned tasks.

The VE was modeled by merging different sources of data: (1) LOD2 CityGML model with textures for the city blocks, which are processed and transferred to Unity3D as FBX model; (2) detailed BIM of one building (LOD400), and (3) virtual objects (e.g., office equipment). Furthermore, unifying the coordinate system of all the EV contents and the real world objects is done to facilitate integration and navigation in both the AR and IAV environments. This step required locating the 3D contents on a base map that is already georeferenced. The georeferenced data can be provided by either using geo-tagging supported devices (e.g., iPad) or applying the following geo-referencing steps: (1) Create a GIS-based map, (2) Collect data, and (3) Import data based on XRefs technique (Revit 2018) which most CAD and BIM-based modeling tool have. After storing BIM data in the *BIM database*, the geometric model is used to create the VE using the game engine.

Based on the method discussed in Section 3.5, four separate databases are assigned to store different types of data including the facility BIM data, registered feature-based tracking data, defects data, and tasks data. The following subsections explains how these different data types are prepared. In this research, FM BIM and non BIM data were merged from different sources and integrated using standard formats as discussed in Section 4.3.

6.3.1 Facilities BIM-based modeling and integration

Unifying the coordinate systems of all the EV building contents and the real world mobile and the static objects is important step to facilitate integration and navigation in both the AR and IAV environments. This step requires locating the 3D contents on a base map that is already georeferenced. The VE contents used in CBIM3R-FMS are developed using Autodesk Revit (Revit 2018) for BIM modeling, Autodesk InfraWorks 360 (InfraWorks 2018) for merging the multisource BIM models (including CityGML, BIM and other virtual objects), Unity3D 5.6.1 (Unity3D 2018) for 3D VE authoring and system development, and Vuforia 6.2 (Vuforia 2018) for creating feature-based tracking data. Figure 6-5 shows the main steps used to create the georeferenced facilities models database.

The georeferenced model is converted as FBX model which can be used directly in IAV module. The georeferenced data can be provided by either using geo-tagging devices (e.g., tablet) or applying the following geo-referencing steps: (1) Create a GIS-based map, (2) Collect data, and (3) Import data based on XRefs technique (Revit 2018) which most CAD and BIM-based modeling tool have.

Before interacting with the facility data (Graphical and non-graphical), it is important to geo-reference these data to facilitate the collaboration between stakeholder. For example, the facility manager, based on the target workspace, may search for nearby equipment that is tracked by indoor GPS. This step can save time and improve productivity.

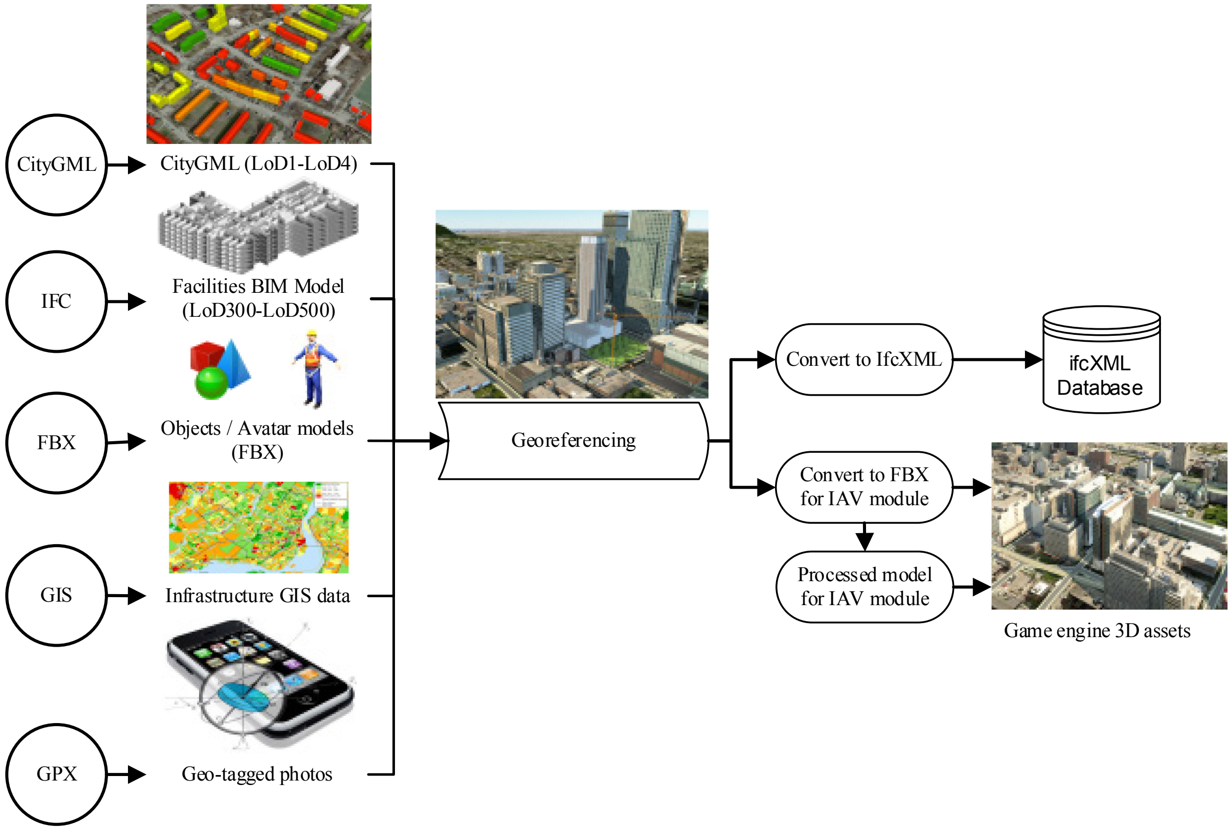


Figure 6-5 BIM-based large-scale facilities modeling

After storing BIM data in the *BIM database*, the geometric model is used to create the VE using the game engine. The large-scale facilities model used in this research is relying on multisource geometric and non-geometric data. Figure 6-6 shows the integrated BIM and CityGML models.

Figure 6-7 shows the BIM and CityGML combined large-scale model within Unity3D. The 3D multisource data integration is processed using Autodesk InfraWorks 360, then transferred to Unity3D as FBX model. The FBX format keeps the necessary information including elements IDs and the hierarchy structure of the original model.

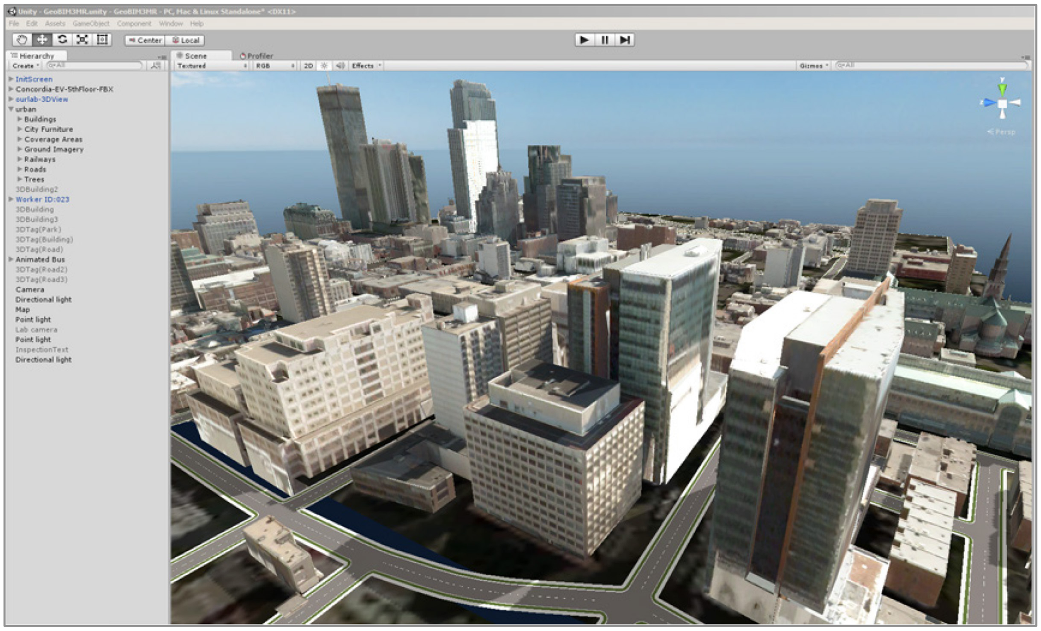


Figure 6-6 Large-scale facility model based on CityGML data

It is important to keep both the structured 3D data and the unique IDs to integrate with the BIM-based attribute database.

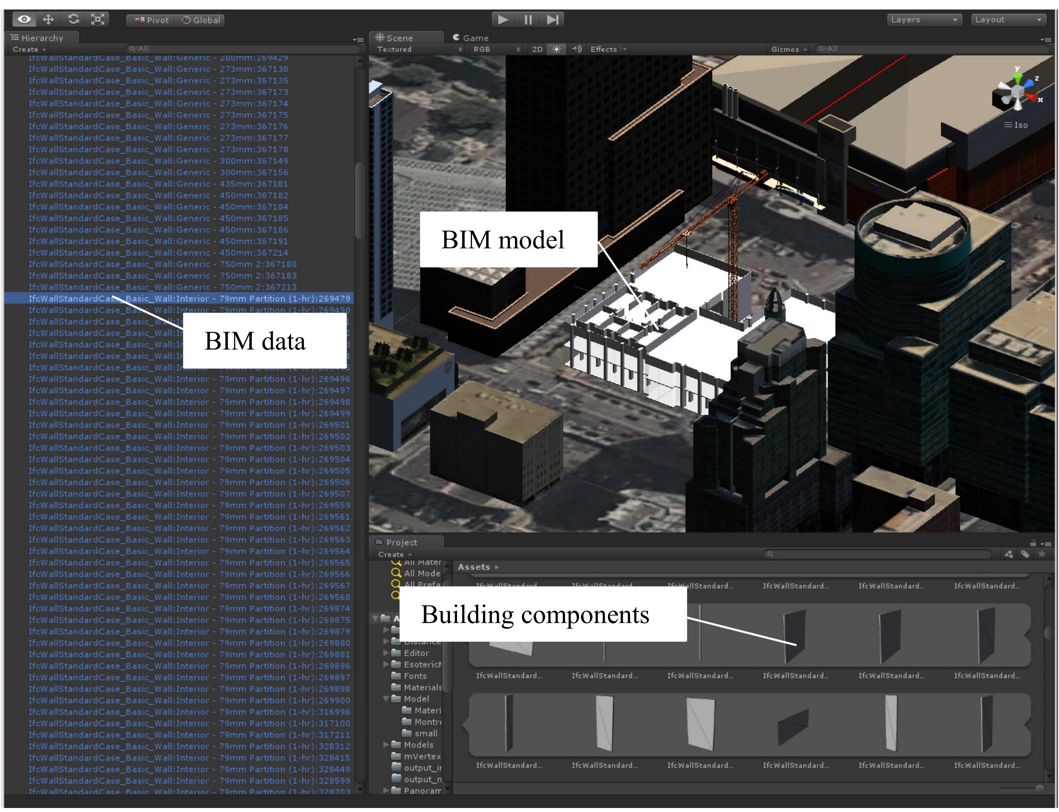


Figure 6-7 BIM and CityGML data integration

Processing BIM model for AR module

The georeferenced model requires an additional step to be used in AR module. As mentioned in Section 4.3.1, BIM model needs to be preprocessed and optimized for AR module. Figure 6-8 illustrates the process of preparing the BIM-based model for the AR module. As an automatic process, the remodeling starts with loading the 3D model (i.e., FBX format), which inherits the building elements hierarchy from BIM model. Then, converting walls, floor, and ceiling to bounding boxes by destroying the rendering components for these building elements. The bounding boxes are used for interaction with the real enjoinment that the model is georeferenced with as explained in Section 4.3.1. The search starts to find false ceiling elements using the element ID in the hierarchy.

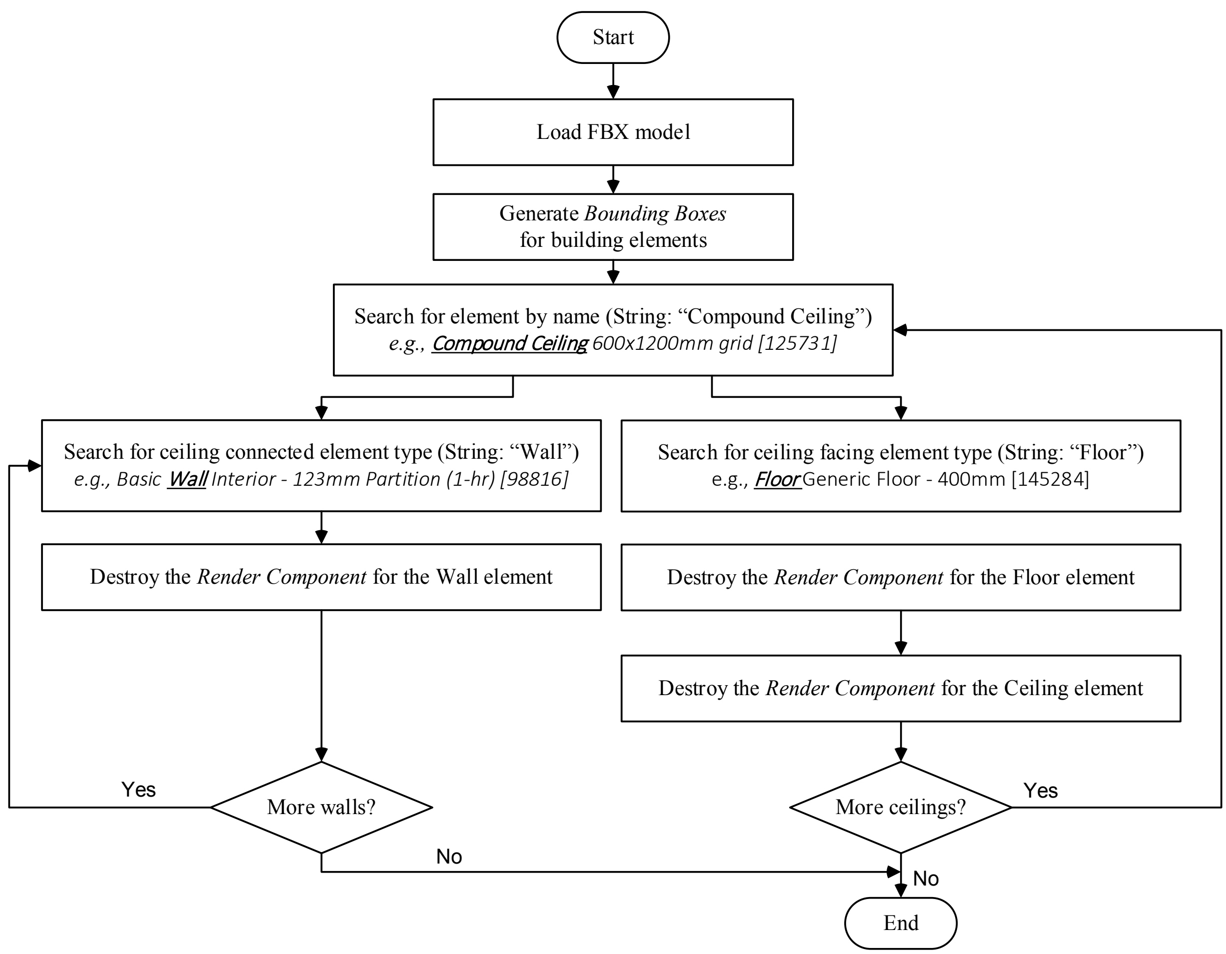


Figure 6-8 Flowchart of processing BIM model for AR module

After that, all building elements type "Wall" that are connected to the identified false ceiling will be selected and their render components will be destroyed. As parallel step, the building element type "Floor", which is facing the identified false ceiling, will be identified using the Raycast method and then its render component will be destroyed. The render component of the false ceiling will be destroyed.

Figure 6-9 illustrates the different formats and sizes for the same BIM model of one floor. The original model is developed in a BIM tool (i.e. Autodesk Revit) with a size of 12.728 MB. When converting the model to IFC and IfcXML, the resulting files have different data formats to describe the hierarchy structure of the model with all its components. For that reason, the IfcXML file is about five times larger than the IFC file. Although IFC and FBX files have almost the same sizes, IFC EXPRESS data format is hard to use for system integration. Therefore, the FBX format is used as the model data format for the system.

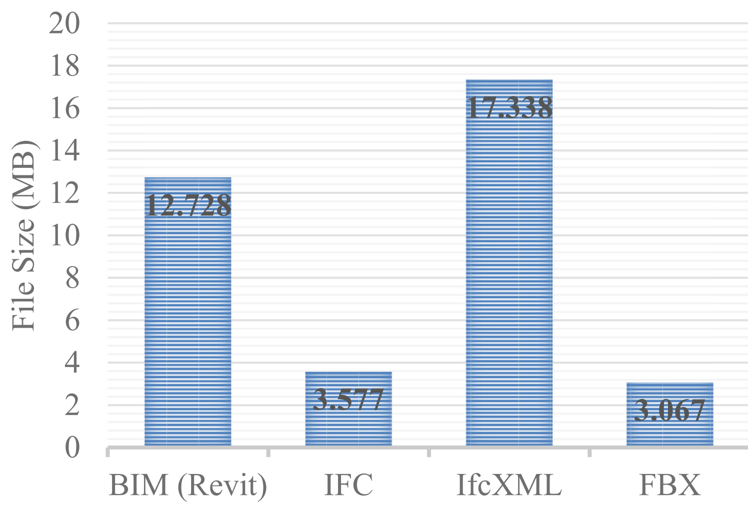


Figure 6-9 Model formats and sizes comparison

As shown in Figure 6-10, the number of triangles and vertices of the FBX model used in the IAV module are 16.6k and 23.1k, respectively. After processing the FBX model for the AR module, these values are dramatically reduced to 3.4k triangles and 10.1k vertices. These two values are important especially when optimizing for low-end hardware.

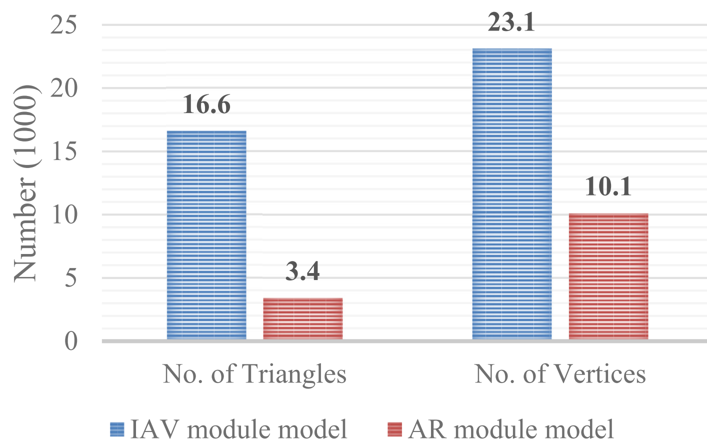


Figure 6-10 Comparison between non-processed and processed FBX model for AR module.

IfcXML parser class

The IfcXML model can be generated using an IFC converter plug-in for Autodesk Rivet 2013. The hierarchy relationships of the model components can be viewed using an XML viewing tools (e.g., XMLSpy (Xmlspy, 2016). Reading these IfcXML data is implemented using a package called *IfcXML Parser*. This package was developed within Unity3D to allow parsing and updating the *BIM database* from any IfcXML2x3 model. This package contains several classes for loading IFC files as well as reading and writing IFC instances in IfcXML representation. Figure 6-11 shows an example of parsing an IfcXML model with the IfcXML parser class. The IfcXML parser package uses Xerces Java parser (apache.org, 2015). Xerces Java Parser provides XML parsing and generation, and implements the W3C XML and DOM (Document Object Model) standards, as well as the SAX (Simple API for XML) standard. The current usage of this parser is to read IFC data of the building attributes and save them in the building database. This building information is used interactively in CBIM3R-FMS database.

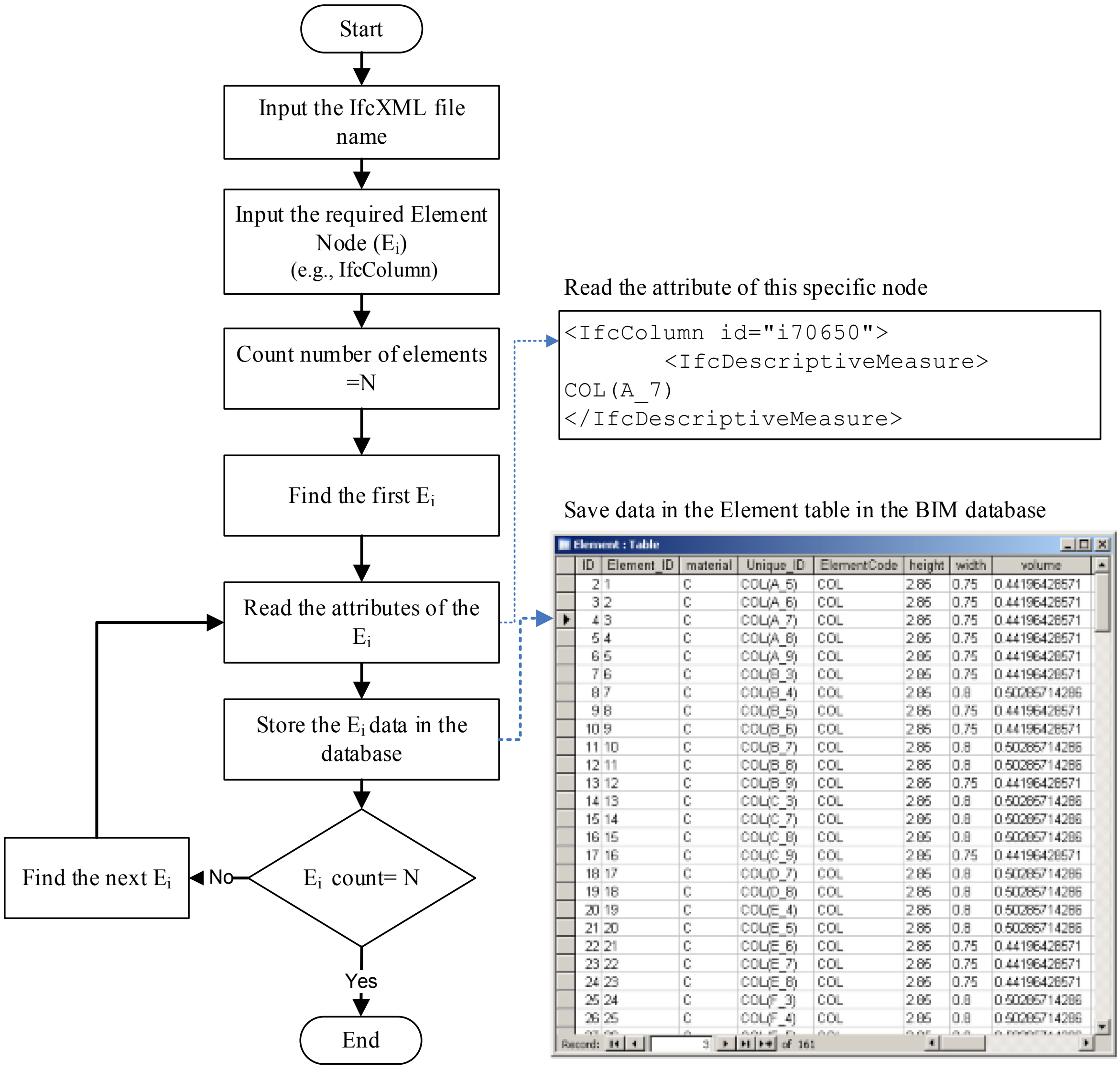


Figure 6-11 Main steps in the IfcXML parser class

FBX-IfcXML integration processes

Figure 6-12 shows the flowchart of picking and highlighting a 3D element. Each object in the VE (e.g. buildings or building elements) has an ID, which is linked with the data stored in the IfcXML file.

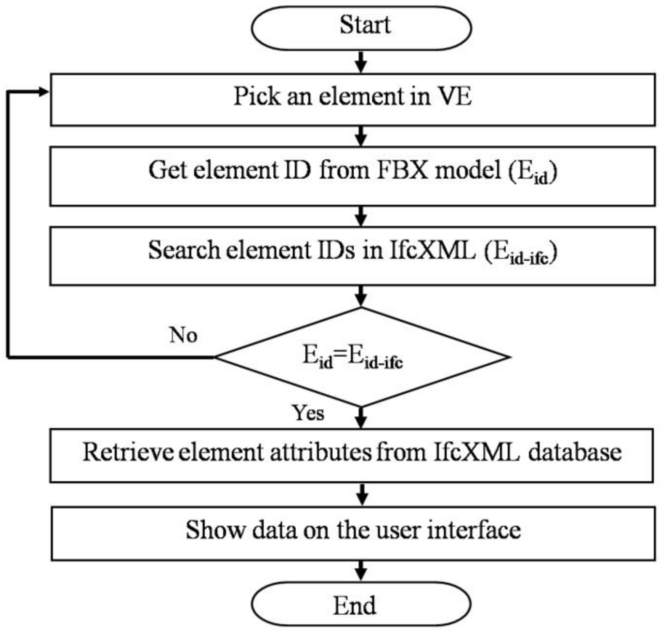


Figure 6-12 Data retrieving process of element attributes

As shown in Figure 6-13, the unique ID (highlighted in red) for a building element (a generic floor) in FBX model is the same as the one in the IFC-based data stored in the database. Upon selection, the building element will be highlighted and a query is activated to retrieve the element information.

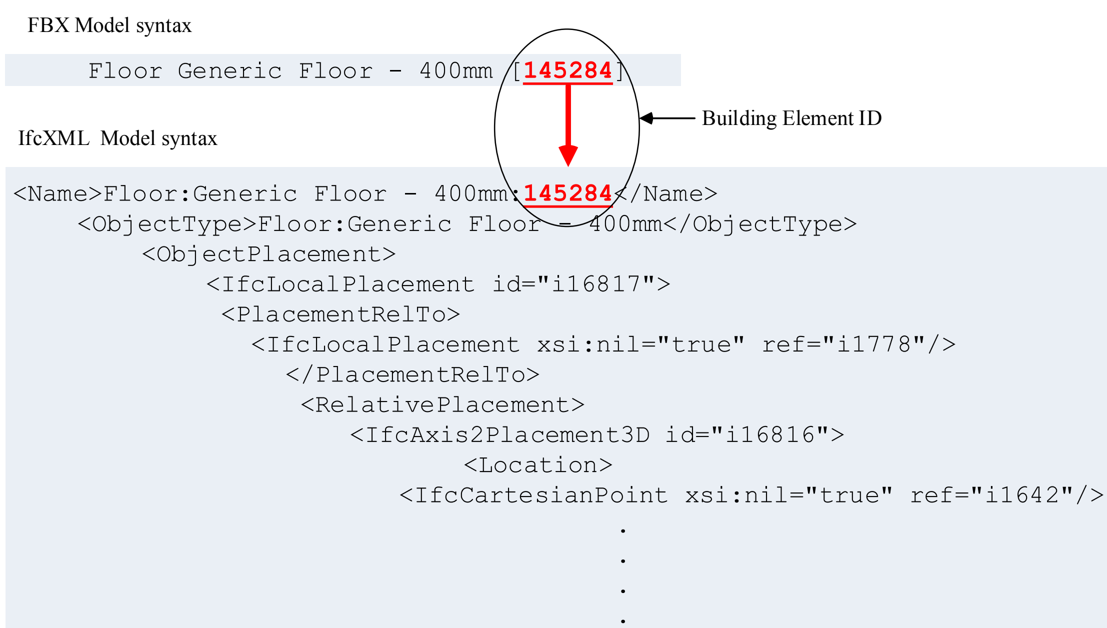


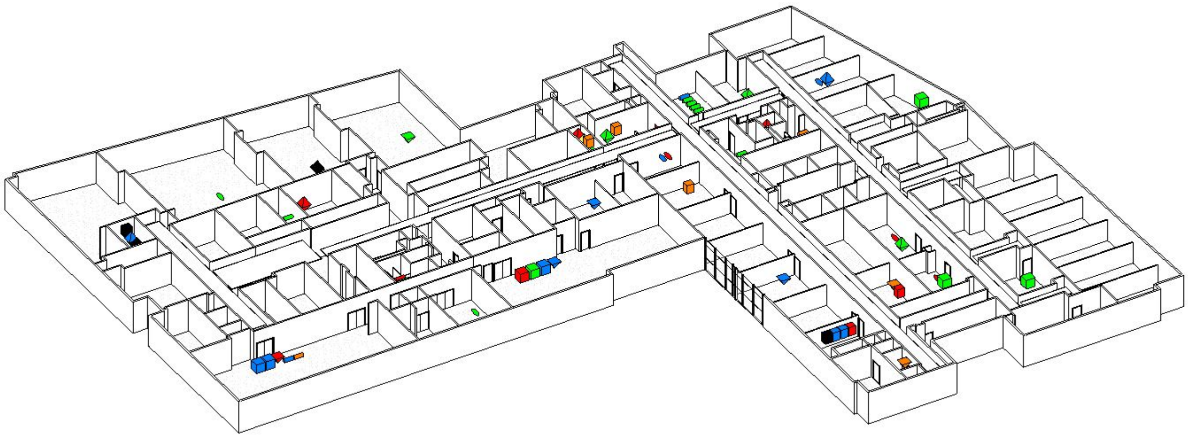
Figure 6-13 FBX and IfcXML data representations

6.3.2 Defect data

The facility users' reported defects are stored in the *Defect database* for the facility manager to assign inspection worker orders for the field workers. Each defect is giving unique ID, type of defect (e.g., corrosion), severity level (i.e., severe, medium, mild), and time and date of the inspection. In addition, each inspected defect record is linked to an inspector name and notes by the inspector. The coordinates of the defect are also stored in the *Defect database*. The ID is generated automatically when the field worker is making a defect using the name of the element, the date, and time of marking the defect (e.g., *BasicWallInterior20180211150655*). This defect naming guarantees the uniqueness of the generated IDs.

6.3.3 Task data

As a valuable historical data, 10-year of work orders' records were provided by the FM Department at Concordia University and added to the work orders' records database. The facility manager's task records, including the historical work orders records, are stored in excel file which is used by both system modules. Figure 6-14 illustrates the spatial visual disruption of the work orders mapped on one floor BIM model of the EV building. This model visualizes the number and type of worker orders in different rooms on this floor during the period of two years, and can be used for future planning of preventive maintenance. The table lists the categories and subcategories of work orders. The 3D symbolic tags were created in Revit. The symbols and colors represent work orders type. For example, for architectural and structural work orders, cubic symbols are used with blue, green and red colors representing repair, install, build orders, respectively. Even though this was a manually time-consuming process to allocate each work order from spreadsheets at the proper place in the 3D model, it is an important step to compare with the proposed visualization method discussed in Section 5.2, where the field worker can view tagged work orders in AR based on his/her real location and the facility manager in VR based on their relative location with less physical and metal loads as concluded in Chapter 8.



Type		Color	Sub-categories
Arch/Building			Repair
			Install
			Build
Cleaning/Ground			CL/Request
			Supply
			Clean/Remove
			Pest
			Recycling
Distribution			Move
			Pickup/Deliver
			Recycle/Shred
Electrical			Breaker
			Bypass Alarm
			Mal/Fail
			Burnt Light
			Inspect/Maintenance
			Install
HVAC			Too Cold
			Too Hot
			No Ventilation
			Noise
			Malfunction/Fail
			Air/Vent
Locksmith			Key/Lock Fail
			Malfunction/Fail
			Install
			Door Jams
Plumb/Mech			Blockage
			Leakage/Flood
			Inspect/Maintenance
			Malfunction/Fail

Figure 6-14 Visualization of work order records tagged on the BIM model

6.3.4 Hybrid tracking data

Marker-based tracking

Based on the method explained in Section 4.2.1, the marker-based tracking is implemented using VTM. In the hybrid tracking method, the marker-based tracking is not used as a tracking technique for AR but only to fetch the relevant feature tracking data to minimize leading time. Figure 6-15 shows one marker used in the lab where the case study is conducted.

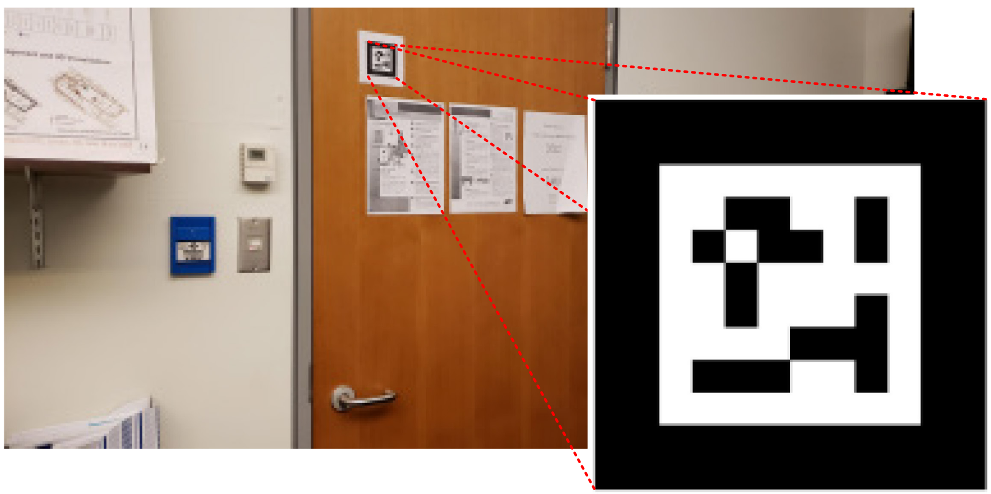


Figure 6-15 Marker used for retrieving relevant marker-based tracking date

In Unity3D environment, The Image Target Behaviour script attached to the marker image has five parameters and their settings are shown in Table 6-1. These parameters have specific setting for each marker including the type, database name, image name, and its physical width and height. In this research, all image targets are set as predefined type. The Vuforia Cloud Recognition Service (Cloud Reco) is another class image recognition method that enables developers to host and manage image targets online.

Table 6-1 Image target parameters setting in Unity3D for the Marker

Parameter	Type	Database	Image Target	Width	Height
Description	Predefined, User Defined, or Cloud Reco	Space ID in the database	Image name	Width of the physical image	Height of the physical image
Setting	predefined	Lab9-415	M9-415	100 mm	100 mm

Feature-based tracking

The tracking data created by Vuforia online tool are used to track the tablet camera pose and align the virtual model with the real world. Vuforia documentation (Vuforia 2018) refer to utilizing some variation of natural feature tracking. Natural features in images with sharp corners and high contrast and details as shown in Figure 6-16. The figure illustrates how VTM detects features and provides its rating accordingly. The yellow cross marks represent the features detected by VTM. Increasing the number of these details in the image creates a non-repeating pattern.

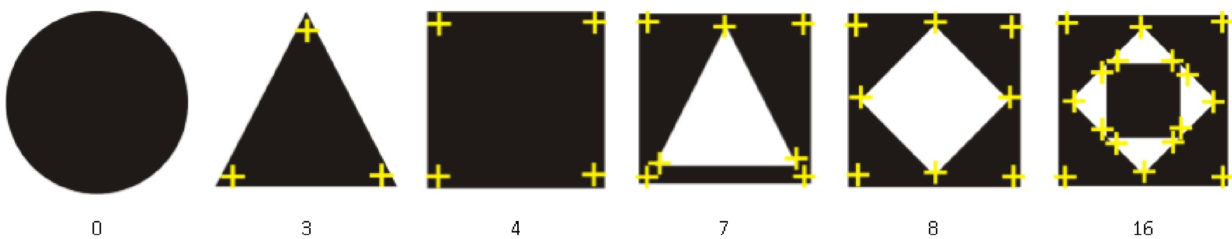


Figure 6-16 Six shapes demonstrating features detected by VTM

As shown, the circle contains no features as it contains no sharp or chiseled details. The triangle contains three features for each one of its corners where the square contains four features and so on. The number under each shape represents the number of features of that shape.

Before registering and developing the tracking data and saving them in the database, it is important to make sure that the virtual elements' edges are aligned and scaled correctly with their relevant elements in the real world. Besides the accuracy of feature-based tracking, this verification step helps in examining the tracking to achieve accurate alignment, which results in a better MR experience. In addition to the task area image (1), four posters were added to create rich features and distinguish between walls. Figure 6-17 shows the locations of the five registered images. Table 6-2 shows the description of feature-based tracking registered images including IDs, dimensions, and the VTM rating for each image. The second raw of the table shows the registered feature which are represented in yellow dots.

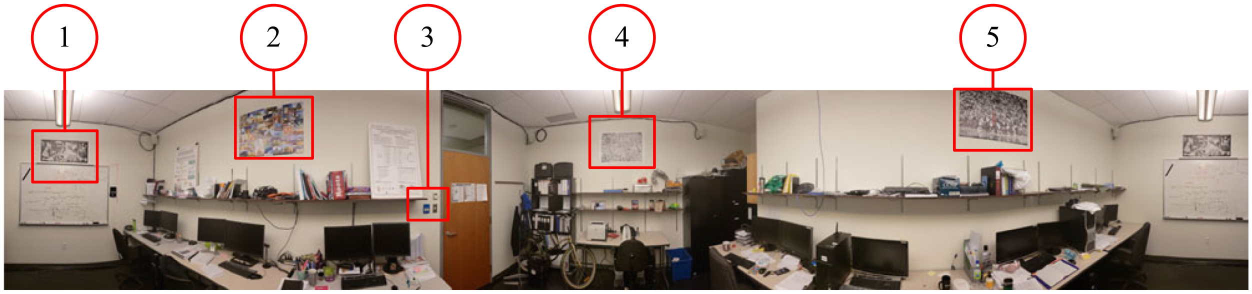
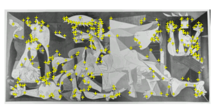
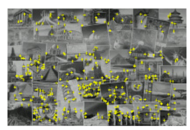
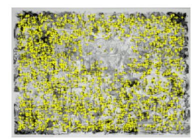
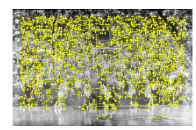


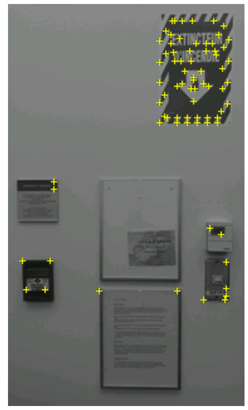
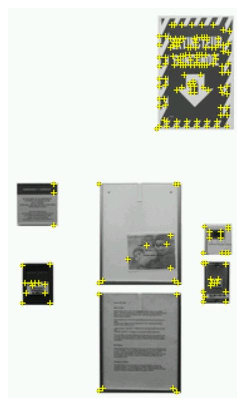
Figure 6-17 Panoramic view for the five registered images

Table 6-2 Description of feature-based tracking registered images

ID	1	2	3	4	5
Image					
Registered features					
Dimensions (cm)	(96x43)	(90x60)	(8.3x11.3)	(84x58)	(90x60)
Number of features	321	362	307	1640	1522
Rating (%)	90	86	84	98	94

The captured five raw images were processed in the web-based Vuforia 6.2 Target Manager (VTM) to create feature-based tracking data including JPG images, DAT files and XML files. The VTM rating is mainly based on three properties: (1) shaping, (2) contrast, (3) non-repetitive patterns and (4) uniform feature distribution. The tracking data are then downloaded and imported as a Unity3D package. Table 6-3 shows the processing steps of a raw image to enhance its trackability which are: (1) adjusting the brightness and contrast; (2) cutting featureless surfaces, and (3) converting to a binary image.

Table 6-3 Image processing effect on enhancing tracking targets

	Colored picture	Binary picture	Trackable features	VTM Rating %
Raw image	 (1)			20
Processed image	 (2)	 (3)		80

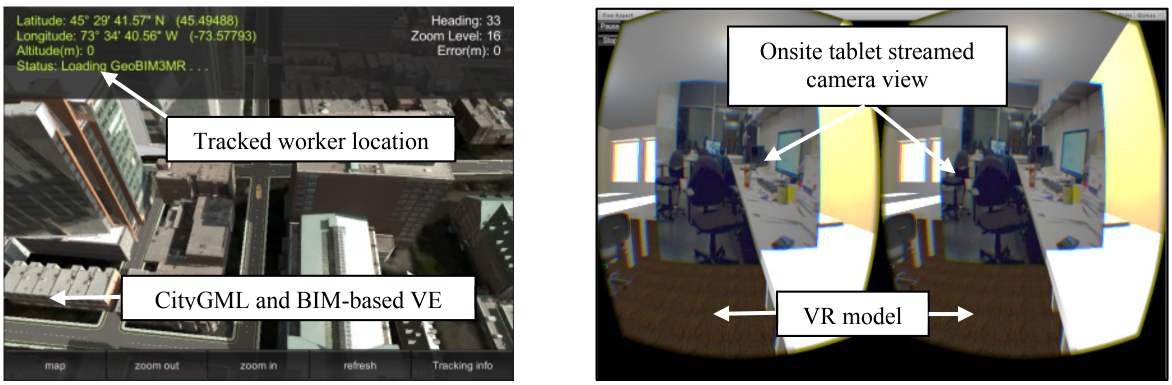
To compare the level of trackability before and after enhancing a raw image, both images were used to create the tracking data using VTM with the foreground in the processed image replaced with white background. In addition, by enhancing the brightness and contrast of the raw image, the tracking obtained a value of 80% in Vuforia rating system for trackable features, whereas non-processed image will obtain only a value of 20%. That does not mean that the non-processed image is not trackable, but the processed one is four times better. However, these values are specific to this image example where the number of unique features are limited. The resulting binary picture shows that the processed image defines clearly the edges, which makes it more trackable. It is important to note that the improvement was reached only using a white background instead of dark background to increase contrast. In addition, using an appropriate texture with a lot of shades considerably raises its rate in VTM because it provides a good distribution and a high number of features.

6.4 CBIM3R-FMS MODULES

As mentioned in Section 3.6, CBIM3R-FMS consists of two modules. Each module can work independently from the other. For example, the facility manager can conduct some FM planning tasks such as assigning tasks for different field workers based on the schedule IAV module. On the other hand, field workers can use the AR module and perform their tasks in a non-collaborative mode. However, when the field worker needs some assistance, he/she can use the IVC mode where the remote expert (i.e., the facility manager) can provide advice considering the shared context. The two module are connected using Remote Procedure Call (RPC) protocol which is coded in C# as shown in Appendix C. RPC protocol is a function call that AR module is using to request and send data from IAV module. RPC is a synchronous operation requiring the requesting application to be suspended until the results of the remote procedure are returned. However, the use of lightweight processes or threads that share the same IP address space allows multiple RPCs to be performed concurrently. The IAV module is set as a server where the AR module is set as a client. The implemented codes can be categorized into four categories: (1) for data sharing between the two modules; (2) for model interaction with the AR and IAV environment including marking and sketching; (3) for data manipulation including interaction with the virtual hatch; and (4) for interacting with the GUI elements as explained in the following sections. These codes were developed based on the IVC method presented in Section 5.2.

6.4.1 Immersive augmented virtuality module

The IAV module of CBIM3R-FMS allows the manager to visualize activities from different views. Figure 6-18(a) shows the large scale VE (i.e., urban and building level) through the Graphical User Interface (GUI) in the IAV module. Figure 6-18(b) shows the collaborative IAV view of the streamed camera view from the tablet of the field worker performing indoor inspection, superimposed on the VR model which improves the situational awareness for the facility manager. Providing a portion of the real world captured by the tablet camera of the inspector can add an important piece of information. This information can be used to visually compare the existing element condition with the stored defect-related information in the *BIM database*. The comparison can be done when the FOV of the AR module and the FOV of the IAV module are matched. Furthermore, the facility manager can update the view of the field worker through the intermediate databases. He/she also can collaborate with the field worker by viewing the FOV of the mobile application as a part of the IAV. In addition, to allow the IAV module user achieve better interaction in the VE, some hardware components are needed to facilitate gesture tracking and visualization, and interaction requirements. These hardware requirements are discussed in Section 6.2. The GUI manipulation allows the facility manager to adjust the location of the GUIs considering his 360° spherical view. For example, the facility manager can move the GUI, using gesture-based direct manipulation behavior to relocate the GUI away from his current FOV to focus on the task. Alternatively, the facility manager can look at the GUI at any time by simply rotating his head.



(a) Large-scale view *(b) IAV view*

Figure 6-18 Examples of office IAV views

6.4.2 Augmented reality module

The AR module is the field worker side application, which is implemented in Unity3D and deployed as an Android application. The application is deployed as an android application and installed on a Samsung Galaxy Tab S2 tablet, which is equipped with WLAN connectivity. This allows the AR application to connect with the databases and to stream location and video data to the IAV module using RPC protocol. To track field workers in the VE, a special script was created to adjust the position (X, Y, Z), and orientation (β) around the Y axis to define the location and heading of the field workers on the map. The AR module is able to track the field worker's camera pose using the hybrid tracking method (discussed in Section 4.2.1). Vuforia Unity Extension (Vuforia 2018) is used to access the registered tracking data inside Unity3D and compare them with the detected features in the images of the video captured by the CMOS 5.0 MP back camera of the tablet. The video is also streamed to the IAV module. The augmentation of the virtual contents can be building elements, elements IDs, or textual information about inspection history stored in the *Defect database*. Considering that the field worker is using one hand to hold the tablet and the other to interact with the AR contents, the GUI was designed to minimize the data entry and maximize the AR view. When the field worker interacts with the GUI, he/she uses the picking behavior to select elements, to mark defects, or to add or retrieve defect information. When the field worker picks a real object through the AR view, the relative georeferenced component's bounding box and the attached data are shown as augmentation. Then, the field worker can pick a specific point on the component to mark a defect. Once the defect mark (e.g., a sphere) is generated, a new window is opened for adding the defect information. The defect mark is georeferenced and its location information is stored automatically in *the Defect database*.

Figure 6-19 shows the AR module view of the system. The view consists of combination of the real camera video, augmenting BIM-based elements, sensory data (i.e., thermal image), textual information retrieved from the *BIM* and *Defect databases*. Minimizing the GUI components of the AR module is important due to the limited screen size. Therefore, the GUI is designed using check toggles to enable or disable the GUI components as needed. The toggle buttons are labelled with letters to describe their functions.

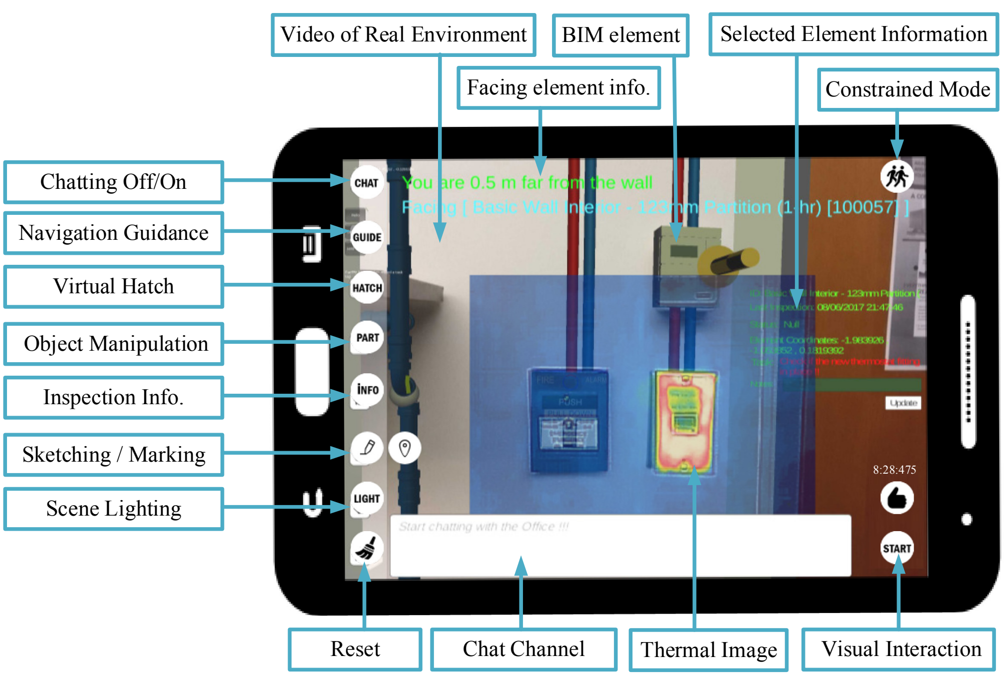


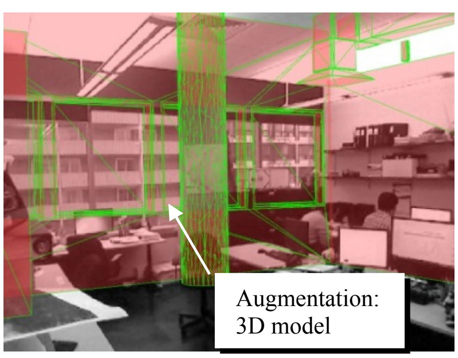
Figure 6-19 Graphical user interface design of AR Module

The main activation button of the GUI is the right bottom button labelled as *START*. Clicking this button activates the left side multi-button GUI, which contains the following: (1) The button *CHAT* for activating a chatting channel between the AR module and the IAV module; (2) The button *GUIDE* for activating the navigation guidance to help the field worker locate georeferenced tagged tasks; (3) The button *HATCH* to activate the virtual hatch (discussed in Section 4.4.1) which can be manipulated with finger dragging functionalities; (4) The button *PART* to place the desired component (e.g. new light switch component); (5) The button *INFO* to visualize the selected element information including its ID, last inspection data, current status and any additional note that the inspector may add; (6) The button with a pencil icon to activate marking or sketching; (7) The button *LIGHT* to enable the georeferenced scene lighting (discussed in Section 4.3.2); and (8) The button with a broom icon to reset marking or sketching and to start a new session of IVC. The upper right button is to allow constrained mode (discussed in Section 3.3) and update the remote IAV module view. The thumb-up button is only used for the usability testing to allow test participants to confirm finishing their tasks for analysis purposes as discussed in Chapter 7.

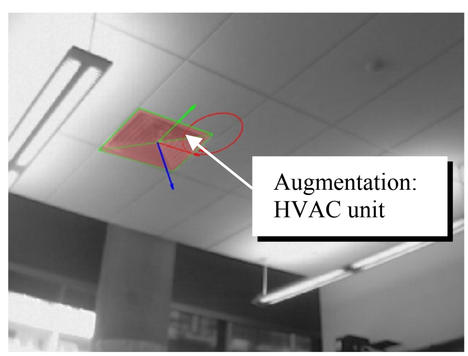
6.4.3 Initial testing

(1) Testing of feature-based tracking

Figure 6-20 shows the accuracy of augmenting the 3D content using feature tracking. The AR module is able to track the user location based on the detected features and augment the relevant information based on this location. More detailed validation of the tracking method is available in Section 7.4.



(a) Augmented column

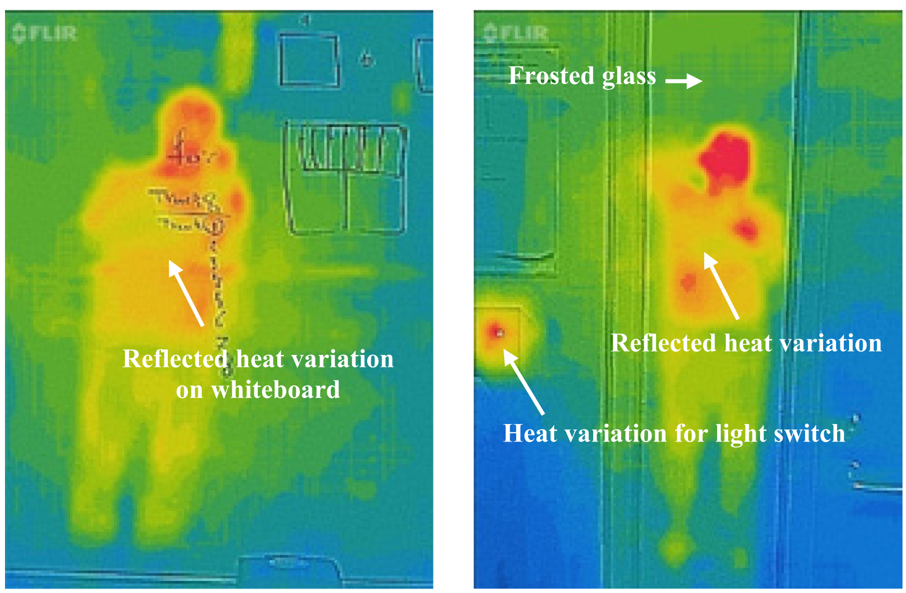


(b) Augmented HVAC component

Figure 6-20 Screenshots of the feature tracking results in AR module

(2) Testing of thermal camera

The thermal imaging is realized using IR thermal imaging sensors that can be attached to the tablet. The heat variations can be displayed as an augmentation on the BIM-based component. On the other hand, using thermal imaging devices can provide inaccurate visual information regarding the surface heat states. For example, when a heat-emitting source is close to a reflective surface, the thermal image from a camera facing the reflected heat on that surface will be affected by the reflection. Figure 6-21(a) shows an example of a thermal image showing heat variations from a human body reflected on a whiteboard facing the thermal camera. Figure 6-21(b) shows heat variations from a human reflected on a frosted glass. Therefore, it is important to identify the heat sources that may contribute to the thermal image. Using BIM data can solve such issues by classifying the heat and cold emitting building components that show high thermal variations. These data can be added to the BIM model as attributes and used where and when needed.



(a) User facing white board (b) User facing frosted glass

Figure 6-21 Misleading thermal camera data

6.4.4 IAV-AR remote interaction

For accurate communication between the facility manager and the field worker, it is important to accurately specify the element or the point of interest on their screen views to avoid confusion. Figure 6-22 illustrates the sequence diagram for the data communication between the two. After updating the VR camera pose in the IAV module based on the detected AR camera pose, both users can point on an element to select or apply marking. These events are captured and the location of the generated marks (e.g., color-coded sphere) can be instantly shared with each other. The geo-referenced marks' location values are streamed using RPCs protocol. It is important to use different color-coded objects as virtual marks to identify who created them.

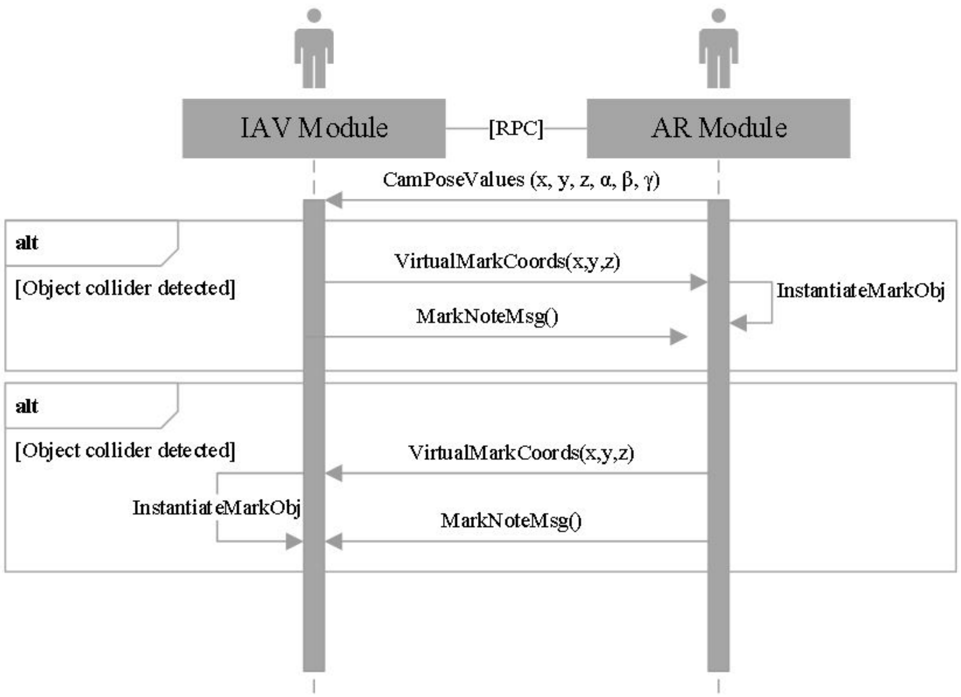


Figure 6-22 Sequence diagram of IAV-AR modules tele-marking

The data types sent through WLAN connection between the AR and IAV modules are: (1) camera pose data as float values, (2) streamed video frames, (3) view picking point coordinates, and (4) textual data. First, the camera pose data are sent from the AR module to the IAV module to update the IAV camera pose in the VE. Second, the video frames of the field worker tablet camera view are used to texture a 2D plane positioned in front of the IAV view. This helps the facility manager at the office to blend real and virtual world for better context awareness of the work environment. Additional layer of thermal images captured by the infrared camera are steamed for texturing the same 2D plane when enabled. Third, the view picking point coordinates can be calculated using ray tracing technique. This technique allows calculating the intersecting point coordinates between a ray generated by picking on the screen and an element collider. These coordinates will be used to instantiate a marking object on each module by its user and instantly stream the same coordinates to instantiate the same object in the other module. When element selection is disabled, the streamed coordinates are used to position the 3D guiding arrow with a normal vector based on the direction of the interaction element. Fourth, the textual information is sent between both modules. This information can be stored in the database to update the selected element user interface on both modules. When applying picking behavior on the IAV module or the AR module, an object collider should be detected to identify a 3D element hit (e.g., a wall). If this condition is satisfied, each module can independently instantiate a 3D object (e.g., sphere) as a mark on the building element. The object should have a different color to differentiate between the local mark and the telemark. To instantiate the mark on the other remote module, the virtual mark coordinates should be received using the RPCs protocol. Figure 6-23 shows the data structure used in remote marking between AR and IAV modules.

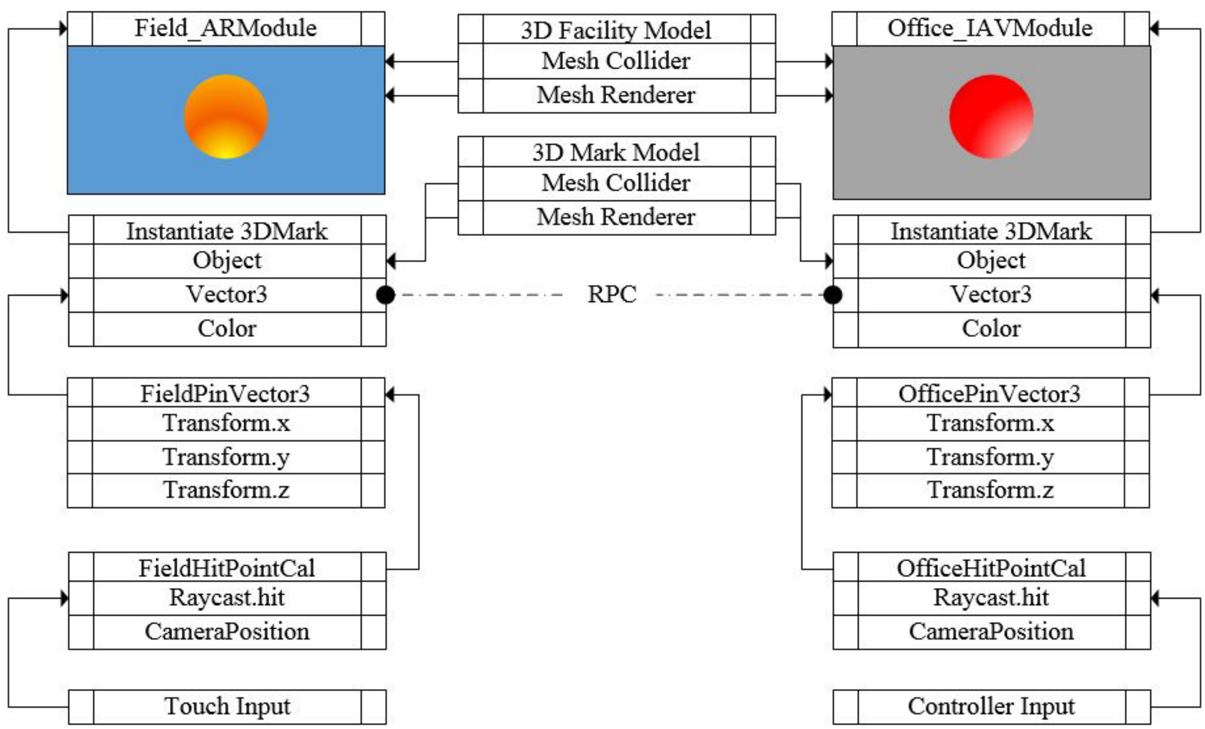
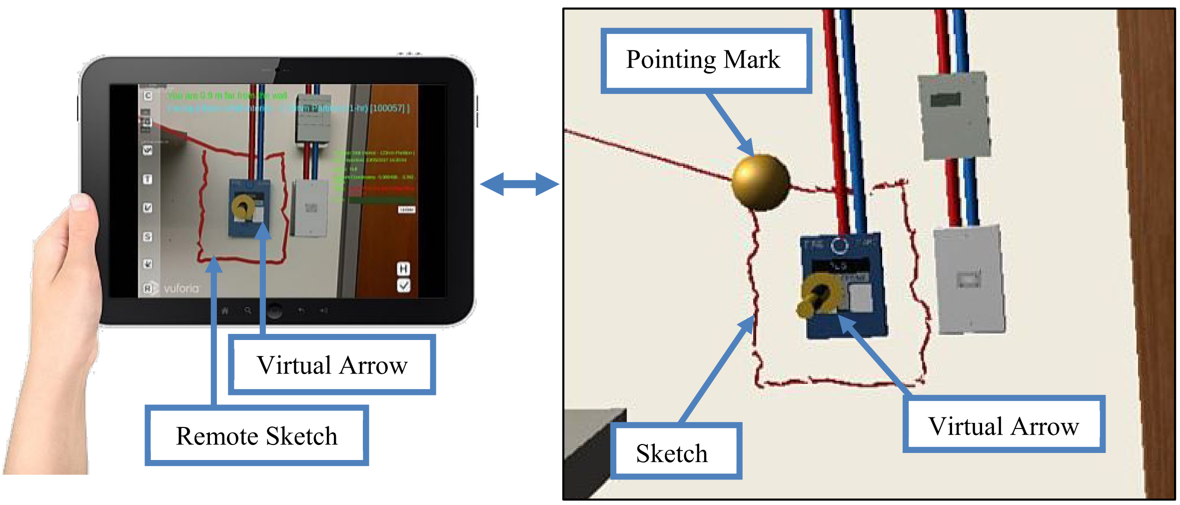


Figure 6-23 Data structure for AR-IAV modules telemarking

The 3D marking model is used to instantiate 3DMark object that has mesh collider and mesh renderer. Then, the instantiated 3DMark has vector3 data and a specific color for each module to avoid confusion. The vector3 data is shared between the two modules using the RPC protocol over Wi-Fi channel. For interaction, the AR module uses touch-based interaction to instantiate the mark, where the IAV uses the controllers' buttons as explained in Section 6.4.1. The intersecting hit point between a ray extended from the camera pose and the target surface is used to position the mark.

Figure 6-24 illustrates the remote marking and sketching. Figure 6-24(a) shows the AR module view with the remote mark and the remote sketch done by the facility manager using the IAV module shown in Figure 6-24(b). The yellow arrow is used for the remote marking and the red line is used for the remote sketch. Both users are seeing the same marking and sketching in real time which allow them to refer to the same building element or to an area of interest to perform the assigned task.



(a) Remote marking and sketching (AR Module view)

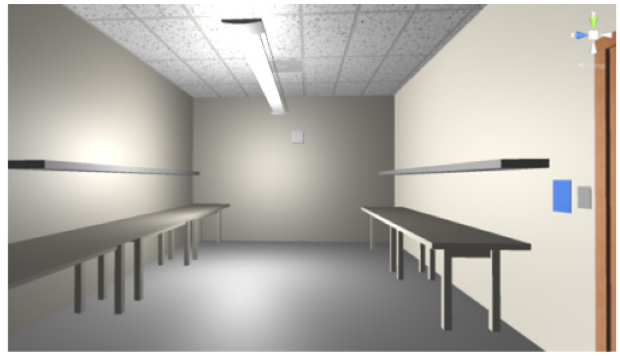
(b) Local marking and sketching (IAV Module view)

Figure 6-24 IAV-AR remote marking and sketching

6.5 CASE STUDY

The case study was implemented at Concordia University's EV Building to demonstrate the validity of the proposed method. In this case study, FM required data from different sources are integrated using a standard format. Figure 6-25(a) shows the real view of a research lab, where Figure 6-25(b) shows the BIM-based virtual model of the same lab.

(a) Real view of the research lab



(b) BIM-based virtual model

Figure 6-25 Research lab real and virtual views

The large-scale facilities model used in this research is relying on multisource geometric and non-geometric data. The CityGML model with textures for the city blocks of the downtown area of Montreal is based on data provided by the city (Ville de Montréal 2017). CityGML allows creating deferent LODs for the 3D environment for an urban context. CityGML data were used as the base model for CBIM3R-FMS. The 3D multisource data integration is processed using Autodesk InfraWorks 360, then transferred to Unity3D as FBX model (Figure 6-26).

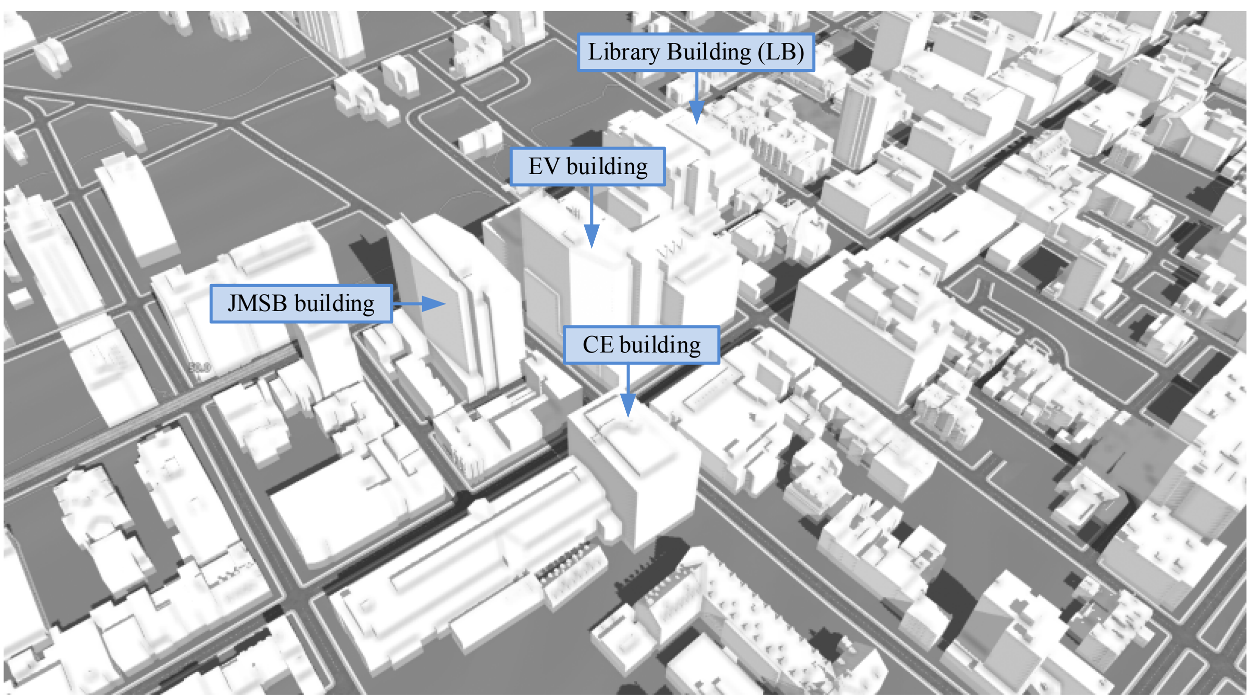
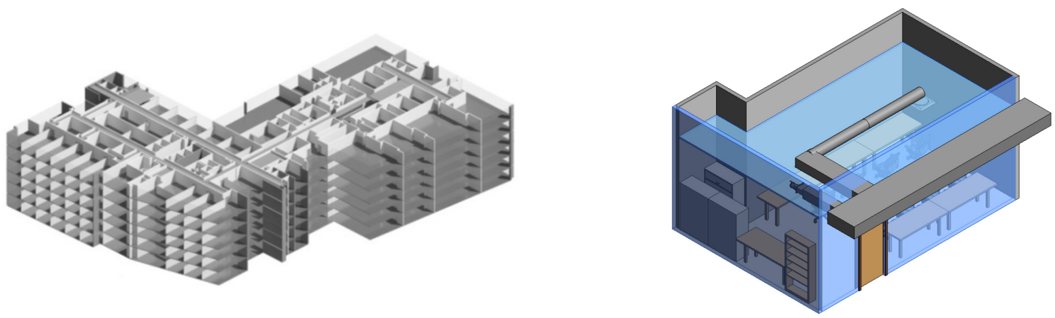


Figure 6-26 CityGML model of the University campus area

In this case study, defects are attached to specific components in the VE using Unity3D. The model was developed in Autodesk Revit (2013) for one floor of the EV building at Concordia University (Figure 6-27(a)) and adding one detailed BIM model (LOD 400) for a research lab in the same floor (Figure 6-27(b)). Also, the defects are considered as components of the 3D model. Other data are added regarding the maintenance procedures, such as the condition and last inspection date of the element that has the defect.



(a) BIM model (LOD300) of the EV building (b) Detailed BIM model (LOD400) of a lab

Figure 6-27 Multilevel BIM models for the EV building

The unique ID for a building element in FBX model is the same as the one in the IfcXML-based data stored in the database. When an element is selected in Unity3D environment, the building element is highlighted and a query is activated to retrieve the element information. In the Revit view, the name of the element is presented in the property tab where the element ID number is queried by the IDs of Selection on the Inquiry panel. After building model is converted to FBX and imported into Unity3D, the element name and ID number are combined into single parameter (i.e., element name [element ID number]), which can be shown on the model hierarchy tab.

6.6 SUMMARY

In this chapter, the implementation of the proposed methods is discussed and detailed description about the development of the CBIM3R-FMS is presented. The system software and hardware requirements are discussed in Sections 6.2.1 and 6.2.2, respectively. The processes of developing multisource data, including BIM modeling and integration, defects data, tasks data, and hybrid tracking data are discussed in Section 6.3. As the main development part for the CBIM3R-FMS, the AR and IAV modules are fully implemented and discussed in Section 6.4. The interaction visual collaboration between the field worker and the remote office modules is implemented and discussed in Section 6.4.4.

In this research, the case study considers only the indoor FM scenarios due to the fact that feature-based tracking is more applicable indoor where less occlusions and reflections exist. The initial testing proved that hybrid tracking is a suitable tracking method for indoor environments considering unique and fixed features. The full validation of the hybrid tracking method is discussed in Section 7.4.

Furthermore, augmenting the field worker view with sensory data (e.g., thermal imaging) can help the decision making in mobile situations. The multi-layer view presented in Section 4.4.2 is implemented and discussed in Section 6.4.2 and validated in Section 7.2. Full details and discussions about the validation of the implemented methods presented in this chapter is discussed in Chapter 7.

CHAPTER 7 VALIDATION

7.1 INTRODUCTION

The objective of this chapter is to validate the efficiency of the proposed framework discussed in Chapter 3, as well as the hybrid tracking, visualization and IVC methods discussed in Chapters 4 and 5. To achieve this, a test scenario was prepared as discussed in Section7.2.1. The usability testing was conducted by selecting random participants with some knowledge of FM inspection and maintenance tasks as described in Section 7.2.2. Overall discussion about the usability testing is presented in Section 7.2. There are two parts of the validation which are: (1) validating the effectiveness of CBIM3R-FMS and (2) validating the accuracy of hybrid tracking. For effectiveness measurement, the time, errors and accuracy of interaction data related to the marking and sketching are captured and used to measure the efficiency and accuracy levels of the remote IVC between the AR and IAV modules.

The participants are asked to perform 17 tasks. The first eight tasks are non-collaborative mode and tasks from nine to 17 use the IVC mode. In the first mode, the participant playing the role of the field worker performs simple tasks on his/her own without assistance from the facility manager. In the second mode, the field worker is supported remotely by the facility manager in the IVC mode. The validation is done based on testing three types of tasks: tag finding tasks, interaction tasks, and collaboration tasks. In the tag finding tasks, the field worker is asked to navigate and find assigned tasks with and without visual guidance support from the system. The participant playing the role of the facility manager is asked to perform the same navigation task. In the interaction tasks, the field worker and the facility manager are asked to mark and sketch on their AR or IAV view, respectively. The time, number of errors and accuracy are calculated to measure the performance. In the collaboration tasks, the field worker interactively collaborates with the facility manager in the IVC mode to perform the assigned tasks. During the collaboration session, they mark on the same specific element in their different environments and sketch around a specific area. The time, number of errors, and accuracy of marking and sketching are captured, and analyzed.

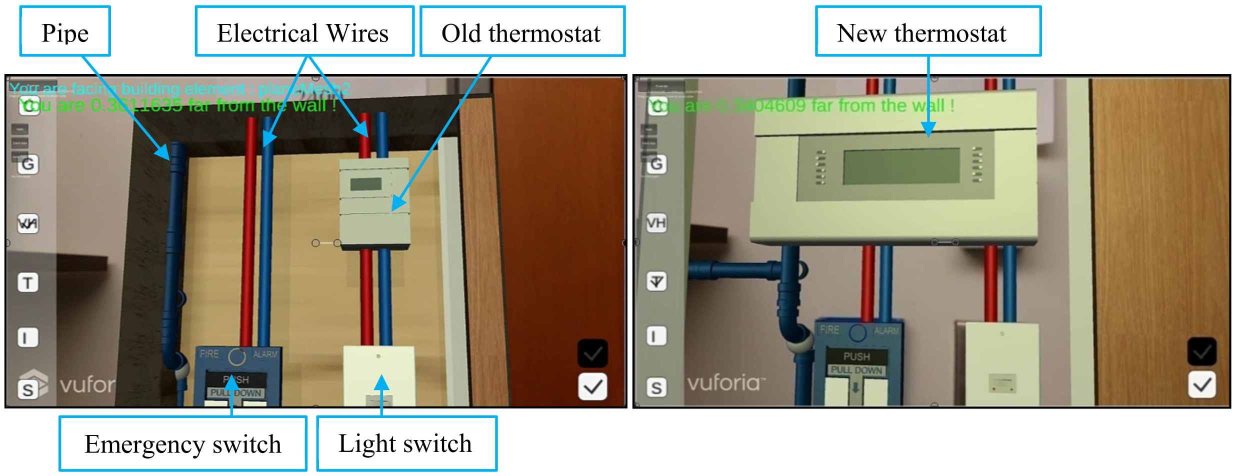
After finishing all required tasks, the participants are asked questions targeting the specific module they are using. The questionnaire consists of two parts as presented in Section 7.2.3. After collecting the testing data, an Analysis of Variance (ANOVA) is used to compare the means of two groups of observations (Turner and Thayer 2001) and check if there is significant difference between the two groups using the different test conditions (i.e. collaborative vs. non-collaborative). The results of the statistical analysis are discussed in Section 7.2.4. Furthermore, the validation of the system effectiveness is measured and discussed in Section 7.3. The hybrid tracking method is validated and discussed in Section 7.4. An overall summary and conclusions about the validation are discussed in Section 7.5.

7.2 USABILITY TESTING

As a validation of the CBIM3R-FMS approach, a simple field task has been planned. In this task, the field worker is asked to perform the same task using the CBIM3R-FMS with and without enhanced visualization support including the virtual hatch, guiding arrows and sensory data. Based on the output of the two tests, the collected data were classified based on the percentage of errors occurred, time to finish the task, and the easiness level as indicated by the field workers.

7.2.1 Test design

The usability testing presented in this chapter is done by 30 participants to evaluate the AR and IAV modules. For each test, two participants are asked to perform the 17 tasks in each module. Each test has two sessions. In the first session, one participant uses the AR module as a field worker and the other uses the IAV module as a facility manager. They both use their modules based on the two testing conditions. In the second session, they switch their roles and each one repeats the test with the new assigned module. The main task used in this test focuses on a reinstallation task where the field worker is required to replace a thermostat attached on a wall. Figure 7-1(a) shows the old thermostat that should be replaced by the new model shown in Figure 7-1(b). The developed system helps the field worker to check the installation conditions. Before installing the actual new thermostat, based on his/her judgment, the field worker can use his/her finger to position the new virtual thermostat in a suitable place by avoiding clashes with nearby visible objects (i.e., emergency switch and light switch) and invisible objects inside the wall (i.e. water pipes that emit heat). The IVC mode allows the facility manger to provide support to the field worker by visually guiding him/her throughout the test tasks.



(a) Old thermostat (real) (b) New thermostat (virtual)

Figure 7-1 AR module views of the old and new thermostats.

As shown in Figure 7-2, by augmenting the thermal image, the field worker can relate to the heat emitting source and move the new thermostat accordingly. In addition, the support from the facility manager at the remote office was done by sketches from the facility manager to help the field worker position the new thermostat at a suitable place.

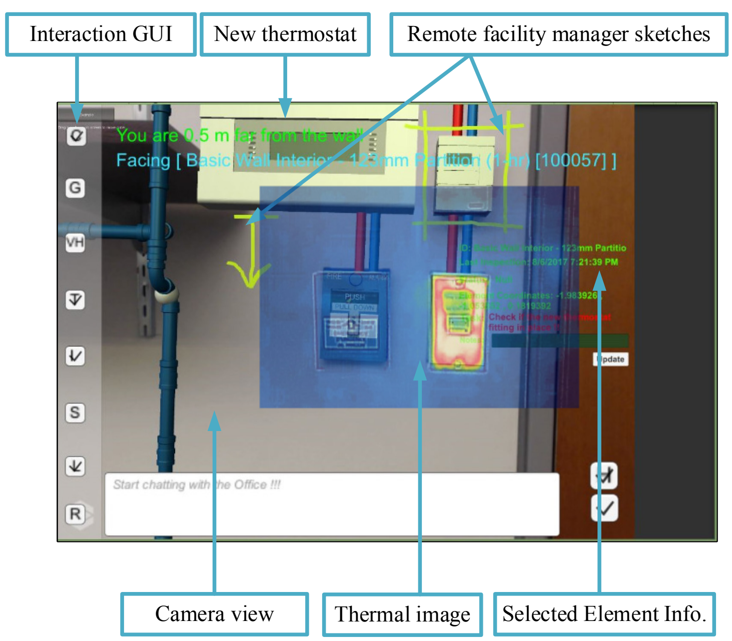
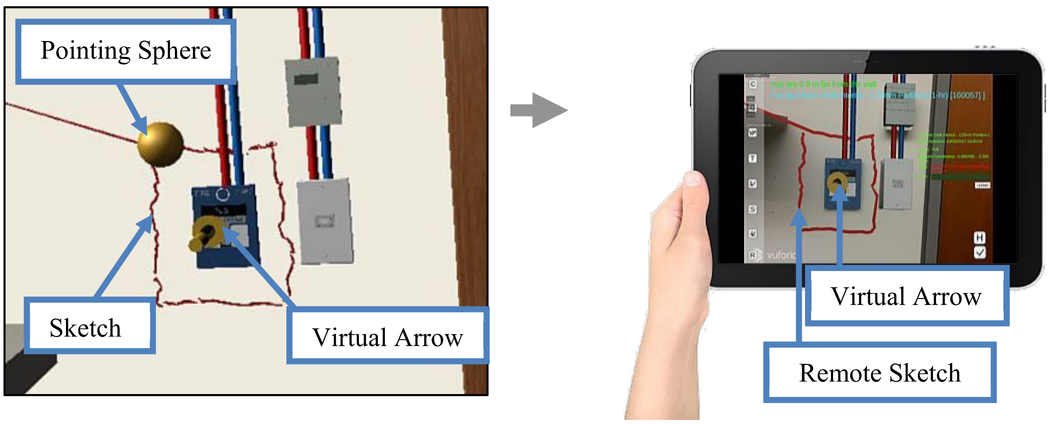


Figure 7-2 Thermal image overlay in AR module view.

Figure 7-3(a) shows the mark and sketch in the IAV module positioned on the BIM model. Figure 7-3(b) shows the AR module view with the remote mark (i.e. yellow arrow) and a sketch (i.e. red line) done by the facility manager. The yellow sphere mark represents the point where the facility manager is pointing in the VE.



(a) Remote marking and sketching (AR Module view)

(b) Local marking and sketching (IAV Module view)

Figure 7-3 IAV-AR remote marking and sketching

After signing the consent form, each participant is given 10 minutes to familiarize himself/herself with the AR or IAV module. As a first step, the participant is introduced to the usability test scenario and its tasks. Table 7-1 shows all the tasks for each module user. In the second step, the participant using the AR module is asked to independently perform seven consecutive tasks (Task 2 to Task 8). The propose of these tasks is to measure the user performance without remote assistance considering the physical constraints including space availability, nearby electrical wires and heat-emitting sources that may affect the thermostat. Then in the third step, the AR module user starts using the IVC by using the constrained mode (Task 9). The remaining tasks (10 to 17) include the two modules interaction where the tasks depend on each other. The installation date is captured automatically and the field worker can add notes to the *Task database* for the facility manager to review. The time to finish each task is recorded by the system in the *Task database*. Based on the time recorded and the answers of the questionnaire, statistical analysis is performed to measure: (1) The effectiveness of CBIM3R-FMS, which includes the accuracy and completeness with which participants achieve specified goals; (2) Its efficiency and the time used by the participants to achieve the tasks; and (3) The participant satisfaction, which is measured by the comfort and acceptability of use. Table 7-1 includes the means and standard deviations (SD) for the time it took to perform the task and the average number of errors occurred $\bar{E}$ (i.e. the number of unsuccessful tasks), which is calculated as the following:

$$\bar{E} = \sum_{j=1}^{R} E_j / R \qquad \text{Equation 7-1}$$

where *E* is the number of errors occurred and *R* is the number of participants.

Table 7-1 List of tasks and their average time and errors

	No.	Tasks		Purpose	Time (Sec.)		No. of Errors	
		AR Module user	IAV Module user		Mean	SD	Mean	SD
Non Collaborative Mode	1	Idle	Start IAV Module.	Launching the server side first	0.79	0.10	0.00	0.00
	2	Start the AR module & point at the test target area.	Idle	Launching the client side second.	0.77	0.20	0.10	0.31
	3	When the red text turns green, press *GUIDE button* and follow guiding arrow and name the tagged Task No. 1.	Idle	To measure time, errors, and effort needed with Arrow Guidance.	1.22	0.8	0.37	0.67
	4	Keep looking around and name the tagged Task No. 2.	Idle	To measure time, errors, and effort needed without Arrow Guidance.	11.88	4.35	0.60	0.89
	5	Press *INFO button*. Go to Task No. 3 and pick on target element (thermostat) and read element name (green text).	Idle	To measure time, errors, and effort needed to identify an element attributes.	3.05	2.80	0.20	0.48
	6	Press *HATCH button* to switch Virtual Hatch on and reposition it around the target element.	Idle	To evaluate visual depth perception using user feedback in the after test survey.	3.47	2.30	0.27	0.52
	7	Press *LIGHT button* to switch lights on.	Idle	To evaluate georeferenced light effect using user feedback in the after survey	0.66	0.20	0.00	0.00
	8	Press *SKETCH button* to sketch over the appeared triangle drawn on the wall as accurate as possible.	Idle	To measure time, errors, and the accuracy of local sketching.	6.69	1.60	0.33	0.61

Table 7-1 List of tasks and their average time and errors (Continued)

	No.	Tasks		Purpose	Time (Sec.)		No. of Errors	
		AR Module user	IAV Module user		Mean	SD	Mean	SD
Collaborative Mode	9	Press *CONSTRAINED MODE button* to reposition IAV user.	Once positioned, you may press any keyboard key to deactivate constrained mode and use on touch controller gears to navigate around.	To update the IAV user camera pose remotely to its relative real location.	4.99	1.00	0.10	0.31
	10	Idle	Press Key 2 on the touch controller to mark on thermostat (Yellow Arrow)	To measure time, errors, and the accuracy of marking in IAV module.	2.01	1.30	0.20	0.48
	11	Name pointed element (three attempts).	Idle	To measure time, errors, and the accuracy of identifying a remotely pointed element.	1.82	0.84	0.23	0.50
	12	Press *MARK button* on the appeared yellow arrow as accurate as possible.	Idle	To measure time, errors, and the accuracy of marking in AR module relative to the remote mark.	1.02	0.40	0.07	0.25
	13	Pick on the marked element (i.e., Thermostat) and Update its current condition (i.e., Bad, Good, Excellent).	Idle	To measure the errors, and the time needed to update records.	3.76	1.70	0.13	0.35
	14	Idle	Read updated thermostat condition.	To measure the errors, and the time needed to review updated records.	1.17	0.80	0.03	0.18
	15	Idle	Press Key 3 to sketch out over the remote sketch done by the AR user.	To measure time, errors, and the accuracy of following the remote sketching.	4.97	1.00	0.20	0.41
	16	Press *PART button* to place new thermostat inside created sketch.	Idle	To measure time, errors, and the accuracy of placing a building element in its proper place.	5.15	1.30	0.13	0.35
	17	Idle	Press update button to update record.	To measure errors and time needed to update records to allow AR user to see.	1.02	0.30	0.00	0.00

7.2.2 Participants

Thirty participants (22 males and 8 females) have participated in the test. The majority of subjects (19) are aged between 25 and 34. Table 7-2 summarizes the participants' collected demographic information. The majority of subjects (76.67%) have engineering background and only eight participants (26.67%) have FM experience. Furthermore, 60 % of the participants used BIM in their projects. Regarding MR experience, 16 participants (53.33%) reported that they had VR experience and five (16.67%) had both AR and VR experience, whereas nine participants (30.00%) had no experience with both AR and VR. Out of the 30, just nine (30%) reported they are having vision problem. Out of the 30 participants, eight are FM workers (5 electricians and 3 general maintenance workers).

Table 7-2 Demographics of test participants

Variables		Frequency	Percentage (%)
Gender	Male	22	73.33
	Female	8	26.67
Age	18-24	1	3.33
	25-34	19	63.33
	35-44	8	26.67
	45-54	2	6.67
Level of education	High school	6	20.00
	BSc	10	33.33
	MSc	13	43.33
	PhD	1	3.33
Professional background	Engineering	23	76.67
	Non-engineering	7	23.33
FM Experience	Yes	8	26.67
	No	22	73.40
BIM Experience	Yes	18	60.00
	No	12	40.00
Mixed Reality Experience	VR only	16	53.33
	AR only	0	0.00
	AR and VR	5	16.67
	Non	9	30.00
Reported vision problem	Yes	9	30.00
	No	21	70.00

7.2.3 After testing questionnaire

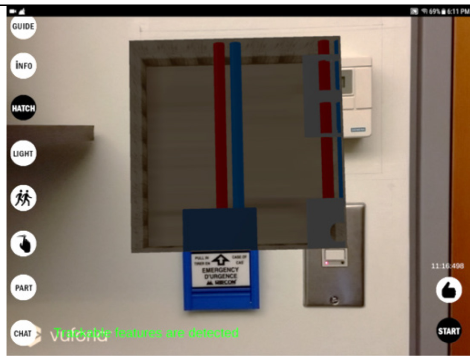
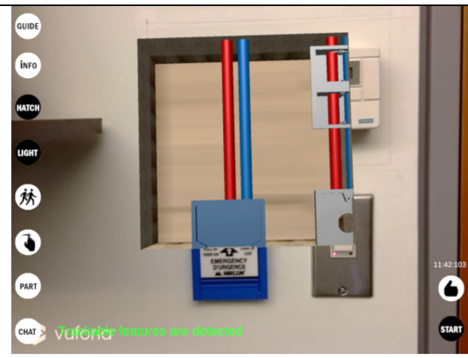
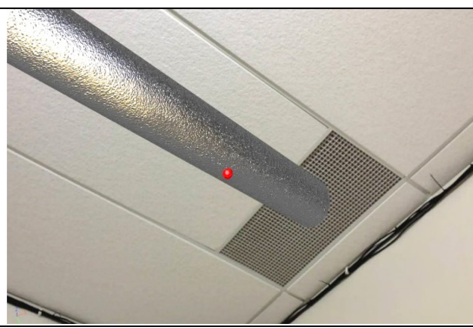
The purpose of conducting the usability testing is to measure the effectiveness, efficiency, and the user satisfaction of the CBIM3R-FMS AR and IAV modules using a questionnaire (as shown in Table 7-3). To identify the test subjects and their knowledge of BIM and MR, the first seven questions are related to the participant gender, age, level of education, professional background and FM experience, sight health, and familiarity with BIM and MR. After answering the first seven questions related to personal information and experience, the participants are asked to provide their level of agreement with the statements presented using a 7-point Likert scale. Each participant was asked overall usability questions (Q8 to Q10), which are adopted from IBM Post-Study System Usability Questionnaire (PSSUQ) (Lewis 1995), about their overall satisfaction level using Likert scale including the user satisfaction of the easiness of completing the assigned task, the amount of time to finish the task, and the support of the visual information. In addition, the mental and physical loads are also evaluated using two NASA's Task Load Index (NASA-TLX) (Hart 2006) questions (Q11 to Q12). To evaluate the collaboration support of CBIM3R-FMS, users were asked their level of satisfaction about specific statements (Q13-Q18). To evaluate the visualization aspects of the system, five more questions (Q19 to Q23) were asked. Finally, an additional question (Q24) was answered optionally about any extra comments or questions related to the task he/she conducted or the CBIM3R-FMS experiences.

The participants are provided clarifications on each question if needed to avoid any confusion or misunderstanding that may affect the final results. The participants are encouraged to provide feedback about their experience in AR and IAV modules and about their tasks without providing them with hints which may affect their personal opinions. Furthermore, in visualization related questions (Q21 to Q23), participants are provided with two pictures for each question (as shown in Table 7-4) to remind them with what they have experienced to avoid confusion.

Table 7-3 After-scenario questionnaire.

	No	Question	Likert scale
IBM (PSSUQ)	8	Overall, I am satisfied with the ease of completing this task.	1 = Strongly Agree to 7 = Strongly Disagree
	9	Overall, I am satisfied with the amount of time it took to complete this task.	1 = Strongly Agree to 7 = Strongly Disagree
	10	Overall, I am satisfied with the support information when completing this task.	1 = Strongly Agree to 7 = Strongly Disagree
NASA-TLX	11	Mental Demand: How much mentally demanding was the task?	1 = Very Low to 7 = Very High
	12	Physical Demand: How much mentally demanding was the task?	1 = Very Low to 7 = Very High
Collaboration	13	I am satisfied with the ease of remote arrow marking.	1 = Strongly Agree to 7 = Strongly Disagree
	14	I am satisfied with the accuracy of remote arrow marking.	1 = Strongly Agree to 7 = Strongly Disagree
	15	I am satisfied with the ease of remote sketching.	1 = Strongly Agree to 7 = Strongly Disagree
	16	I am satisfied with the accuracy of remote sketching.	1 = Strongly Agree to 7 = Strongly Disagree
	17	I am satisfied with the ease of finding the task tag.	1 = Strongly Agree to 7 = Strongly Disagree
	18	Overall, I am satisfied with the AR-IAV interaction experience.	1 = Strongly Agree to 7 = Strongly Disagree
Visualization	19	Overall, I am satisfied with the visual experience.	1 = Strongly Agree to 7 = Strongly Disagree
	20	I am satisfied with the amount of facility information.	1 = Strongly Agree to 7 = Strongly Disagree
	21	*(After showing two pictures of AR and IAV views without and with the Overlaid Thermal Image)* Which view is more visually informative?	1 = With TI support OR 2 = Without TI support
	22	*(After showing two pictures of AR and IAV views without and with the Georeferenced Lights)* Which view is more visually enhanced?	1 = With GL support OR 2 = Without GL support
	23	*(After showing two pictures of AR Module view without and with the Virtual Hatch)* Which view has more depth perception and visually convincing?	1 = With VH support OR 2 = Without VH support
	24	Do you have any other comments, questions, or concerns?	

Table 7-4 Visualization comparison

	Choice No. 1	Choice No. 2
Q21		
Q22		
Q23		

7.2.4 Discussion and statistical analysis

(1) Statistical analysis

Table 7-5 shows the minimums, maximums, medians, means, standard deviations (SD), and different Likert scales of all items based on the subjects' experiment conditions which using different modules. The results show that IAV users are less satisfied (mean=2.17) with the easiness of completing the task (Q8) compared with the AR module users (mean=1.77). In addition, IAV users were less satisfied with the amount of time it took to complete the task (Q9) (mean=2.20) whereas AR module users showed more satisfaction (mean=1.77). The results also show that AR users are more satisfied with the support information they get during the task (Q10) (mean=1.73), where IAV users are less satisfied (mean=2.10). For both mental and physical loads (Q 11 and Q12), the users of AR module users found it less demanding (mean=1.37 and 1.77, respectively) compared with IAV users (mean=1.83 and 2.33). During IVC mode, both the AR and IAV users almost agree about the easiness of the remote arrow marking (Q13) and remote sketching (Q15). However, only AR users are satisfied with the accuracy of remote sketching (Q16) (mean=2.07) while IAV are less satisfied (mean=2.57).

Considering Question 17, the scores indicated that the IAV users did not believe that finding the task tag is easy task in VE (mean=2.50). The AR module users however showed more confident about how easy to find tagged tasks (mean=1.90). During the IVC session, both users have almost similar satisfaction level about the AR-IAV interaction experience (Q18) (mean=1.57 and 1.43) and AR-IAV visual experience (mean=1.43 and 1.53). The AR module users are more satisfied with the amount of facility information augmented on their view (Q20) (mean=1.07), whereas IAV has less satisfaction level (mean=2.30).

Table 7-5 Descriptive statistics for the after-scenario questionnaire.

Question No.	Experiment Condition									
	AR Module					IAV Module				
	Min	Max	Median	Mean	SD	Min	Max	Median	Mean	SD
8	1.00	3.00	2.00	1.77	0.68	1.00	3.00	2.00	2.17	0.79
9	1.00	3.00	2.00	1.77	0.73	1.00	4.00	2.00	2.20	0.89
10	1.00	3.00	2.00	1.73	0.64	1.00	3.00	2.00	2.10	0.71
11	1.00	4.00	1.00	1.37	0.72	1.00	4.00	1.5	1.83	1.02
12	1.00	4.00	2.00	1.77	0.90	1.00	4.00	2.50	2.33	1.12
13	1.00	3.00	1.00	1.33	0.55	1.00	3.00	1.00	1.37	0.56
14	1.00	3.00	1.00	1.47	0.63	1.00	3.00	1.00	1.53	0.68
15	1.00	3.00	2.00	1.57	0.57	1.00	3.00	1.00	1.47	0.57
16	1.00	4.00	2.00	2.07	0.74	1.00	5.00	2.00	2.57	1.07
17	1.00	3.00	2.00	1.90	0.66	1.00	6.00	2.00	2.50	1.38
18	1.00	4.00	1.00	1.57	0.73	1.00	4.00	1.00	1.43	0.68
19	1.00	2.00	1.00	1.43	0.50	1.00	3.00	1.50	1.53	0.57
20	1.00	2.00	1.00	1.07	0.25	1.00	5.00	2.00	2.30	1.18

For Q21 to Q23, all participants unanimously agreed that: (1) having sensory data visualized as a layer in their views is more visually informative for both AR and IAV modules, (2) using georeferenced lighting enhanced the AR and IAV modules view and matches the reality, and (3) the virtual hatch in AR module enhanced the depth perception.

All different variables in the questionnaire were analyzed using a one-way repeated measures ANOVA with an alpha level of 0.05.

Table 7-6 summarizes the results of ANOVA analysis. The results were statistically significant between the different conditions (i.e. AR vs. IAV) of the test for 10 questions. On the other hand, the results indicate that there are similarities for the remaining 6 questions. For example, there was no significant difference when it comes to users' satisfaction about the easiness and the accuracy of remote marking and remote sketching. One exception is that the IAV module users were less satisfied with the level of accuracy of the sketching (Q16). Some of them have indicated that the screen was so sensitive to the finger touch. In addition, both AR and IAV modules users felt that they were supported with visual information during the task and they were very satisfied with the IVC mode.

Table 7-6 One-way repeated measures ANOVA results.

Variables	F-ratio	P-value	Variables	F-ratio	P-value
Q8	4.41	0.04*	Q16	4.42	0.04*
Q9	4.28	0.04*	Q17	4.59	0.04*
Q10	4.40	0.04*	Q18	0.54	0.47**
Q11	4.20	0.05*	Q19	0.52	0.48**
Q12	4.65	0.04*	Q20	31.38	0 .00001*
Q13	0.05	0.82**	Q21	23.2	0.000011*
Q14	0.16	0.70**	Q22	0.34	0.56**
Q15	0.46	0.50**	Q23	47.93	0 .00001*

* The result is significant at $P < 0 .05$ ** The result is not significant at $P \geq 0.05$

Furthermore, Table 7-7 demonstrates the minimums, maximums, means, and standard deviations (SD) for the time of performing the task, which is identifying a building component such as the light switch or the thermostat based on the two conditions. The first condition is without using the IVC mode (as performed in Task 4) and the second condition is with the IVC mode (as performed in Task 11). By comparing the means, it is clear that finding tasks with IVC support took less time (1.82 seconds) which is about 15% of the time for performing the task without the support.

Table 7-7 Descriptive statistics for the time for identifying tagged tasks

	Time (Sec.)	
	Without IVC	With IVC
Minimum	02.02	00.90
Maximum	20.49	03.35
Mean	11.88	01.82
Standard deviation	04.35	00.84

Table 7-8 shows the results of the one-way ANOVA. The results are statistically significant between different conditions of the test.

Table 7-8 ANOVA analysis results for IVC depended variables

Source of Variation	SS	df	MS	F-ratio	P-value	F-critical
Between Groups	2579.25	1	2579.25	14.78	0.0003	4.007
Within Groups	10118.86	58	174.46			
Total	12698.11	59				

SS = Sum Square df= Degree of Freedom MS = Means Square F = F statistic

(2) Participants remarks

Table 7-9 summarizes the participants' remarks about their experience with the AR and IAV modules during the test. Their remarks can be categorized in two categories: positive remarks and negative remarks. Some remarks include recommendations about features they believe are nice to have to improve FM tasks.

Figure 7-4 summarizes the opinions of the eight FM workers about the overall usefulness of CBIM3R-FMS by comparing the current practice conventional method and the IVC method based on five criteria: (1) The easiness of use; (2) Time to conduct the tasks; (3) The accuracy of the information; (4) Collaboration; and (5) The adaptability of the method.

Table 7-9 Summary of participants' remarks

	Positive remarks	Negative remarks
AR module	• Collaborating with a co-worker and sharing his view looks very clear and accurate. • Interacting remotely using marking and sketching saves time and eliminates errors. • Being able to see through the wall using the virtual hatch is very good idea. It looks like a real hatch. • Finding building elements, without looking at maps or complex 3D models, is very interesting and time saving. • BIM-based AR makes inspection and maintenance tasks much easier. • Seeing the hidden electrical wires and marking on them precisely and share this information visually with a remote expert can solve many issues related to critical tasks. • The GUI is easy to use.	• AR-module cannot be used in hands-free mode using AR glasses. • Using heavy and large tablet can be physically demanding for some users. • Needs extra training to avoid making mistakes. • Using touch screen for marking and sketching can be tricky and accidently trigger some buttons.
IAV module	• Multi-layer view is very informative. • The interaction with the remote field worker feels like the user is actually there. • Seeing the remote live video of the real thermostat mapped over the virtual one is very accurate and helpful. • Interacting with remote worker can reduce the time for waiting for approval. • No motion sickness.	• Element search feature is missing. • Needs more training with the controllers. • For visually impaired people, identifying some aspects using the VR glasses presents some challenges without the aid of "their extra pair of eyes". I strongly suggest that this should be considered.
Overall	• The AR-IAV visual interaction experience is very promising.	• Adding audio chatting may save extra time.

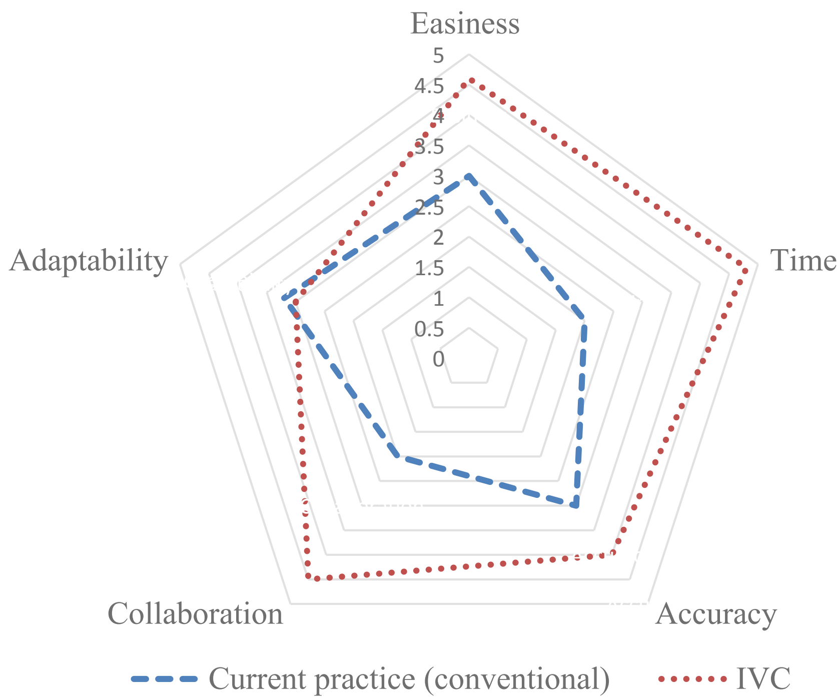


Figure 7-4 Comparison chart between current practice and IVC task performance

By comparing the means of each category, the results showed that the workers preferred using the IVC over what they are using in their current practice. However, they have a doubt about the adaptability of the system. Almost all agreed that using new technologies may expose their privacy and they may feel that they are tracked and all their mistakes can be recorded. Of course the facility managers will disagree since they do not consider this capability as a disadvantage.

(3) Evaluation of the accuracy of remote interaction

To evaluate the interactive collaboration experience using the IVC mode, it is important to evaluate the accuracy of remote marking and sketching with respect to the georeferenced BIM model. First, the facility manager is shown a target point (i.e. the center point of Figure 7-5) and asked to mark on top of it. Second, the new pointing arrow added by the facility manager is shown in the AR module, and the field worker is asked to mark on top of it as accurately as possible.

Then, the following three errors (maximum, minimum, means and the standard deviations) are calculated as shown in Table 7-10: (1) to ground truth target in IAV module, (2) to ground truth target in AR module, and (3) between AR and IAV modules marks.

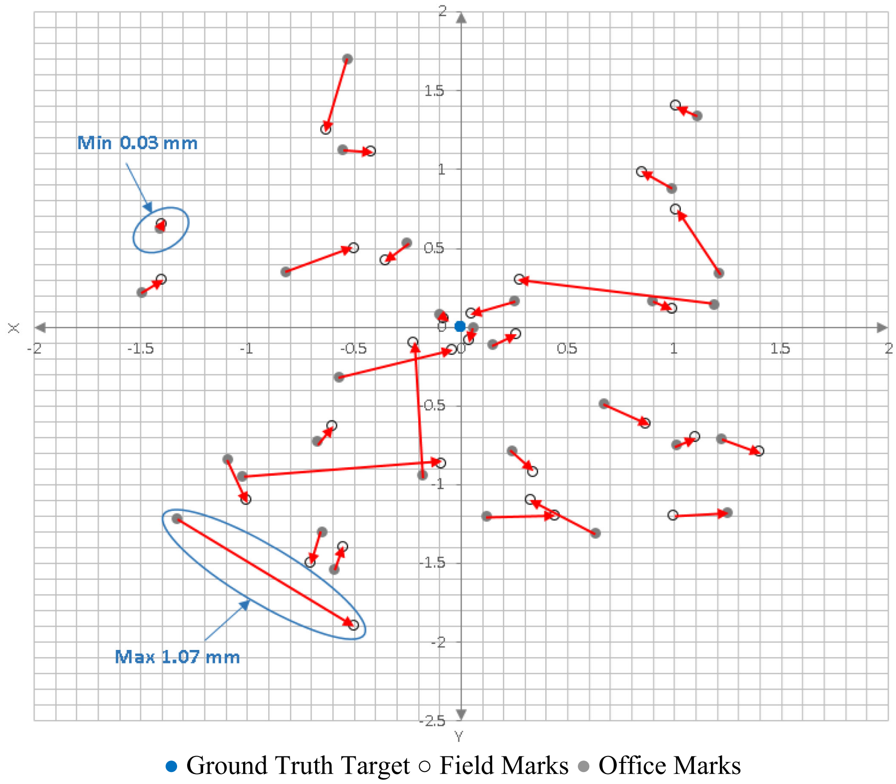


Figure 7-5 Comparison graph between AR module user marking and IAV user marking

The results show that the average error to the target point is 1.03 cm in the AR module and 1.12 cm in the IAV module, and the average error between the AR and IAV marks is 0.31 cm. These values indicate that the level of accuracy is acceptable for pointing on small facility components such as electrical components. Furthermore, the same accuracy is achievable when performing sketching.

Table 7-10 Statistics of errors for remote marking using IVC.

Errors (cm)	**Max**	**Min**	**Mean**	**SD**
To ground truth target in IAV module	1.80	0.06	1.12	0.50
To ground truth target in AR module	1.96	0.09	1.03	0.56
Between AR and IAV modules marks	1.07	0.03	0.31	0.28

Several factors may affect the accuracy of marking related to the AR and IAV modules as shown in Table 7-11. The user skill can be improved by more training as one of the participants indicated. Although all participants had a training session, as mentioned in Section 7.2.1, the results show that some participants had difficulty using the correct controller button for marking and sketching. Others had problems using the touch screen of the tablet and applying multiple touches, which resulted in multiple marks. Also, the incorrect configuration of the VR hardware settings may result in accuracy issues. For example, if the tracking cameras are not configured correctly, the location of the controllers will not be tracked correctly. That means, the ray used for marking and sketching will be casted from a wrong position. The stability of the feature-based tracking is important and may affect the accuracy of the marking and sketching. Flickering augmenting objects or invisible surfaces (i.e., surfaces of the bounding boxes of building elements) can cause inaccurate marking or sketching.

Table 7-11 Identified factors effecting marking accuracy

	Skill	**Hardware**	**Software**
IAV module	User skills of using controllers	VR controllers	HMD and controllers calibration
AR module	User skills of using touch screen of the tablet	Sensitivity of the touch screen	Feature-based tracking

7.3 CBIM3R-FMS EFFECTIVENESS

According to ISO-9241(ISO 1998), product effectiveness is defined as the accuracy and completeness of user goal achievement. To measure the overall effectiveness of CBIM3R-FMS, first the percentage of users who completed their tasks without any errors needs to be calculated using Equation 7-2.

$$\bar{E} = \frac{\sum_{j=1}^{R}\sum_{i=1}^{N} n_{ij}}{RN} * 100 \qquad \text{Equation 7-2}$$

where *N* is the total number of tasks.

R is the number of users performed the task.

n_{ij} is the result of task i by user j; $n_{ij}=1$ if the task was completed, and $n_{ij}=0$, if the task was unsuccessful and user failed to achieve the goal.

Then, the effectiveness statistic error is calculated using Equation 7-3.

$$\sigma_E = \sqrt{\frac{\bar{E}(100-\bar{E})}{R}} \qquad \text{Equation 7-3}$$

Finally, the overall CBIM3R-FMS Effectiveness is calculated using Equation 7-4

$$E = \overline{E} \pm \sigma_E \qquad \text{Equation 7-4}$$

Figure 7-6 shows the effectiveness chart of using CBIM3R-FMS. The percentage of participants who have completed their tasks successfully are shown in gray; the percentage of unsuccessful ones are shown in black. The results show that the overall integral effectiveness E is 90.20% with an effectiveness statistic error (σ_E) margin of ±1.8. Therefore, the overall CBIM3R-FMS effectiveness is determined as good with sufficient degree of confidence according to the scale presented in Table 7-12.

Table 7-12 Effectiveness scale

Very bad	bad	normal	good
0-50%	50-75%	75-90%	90-100%

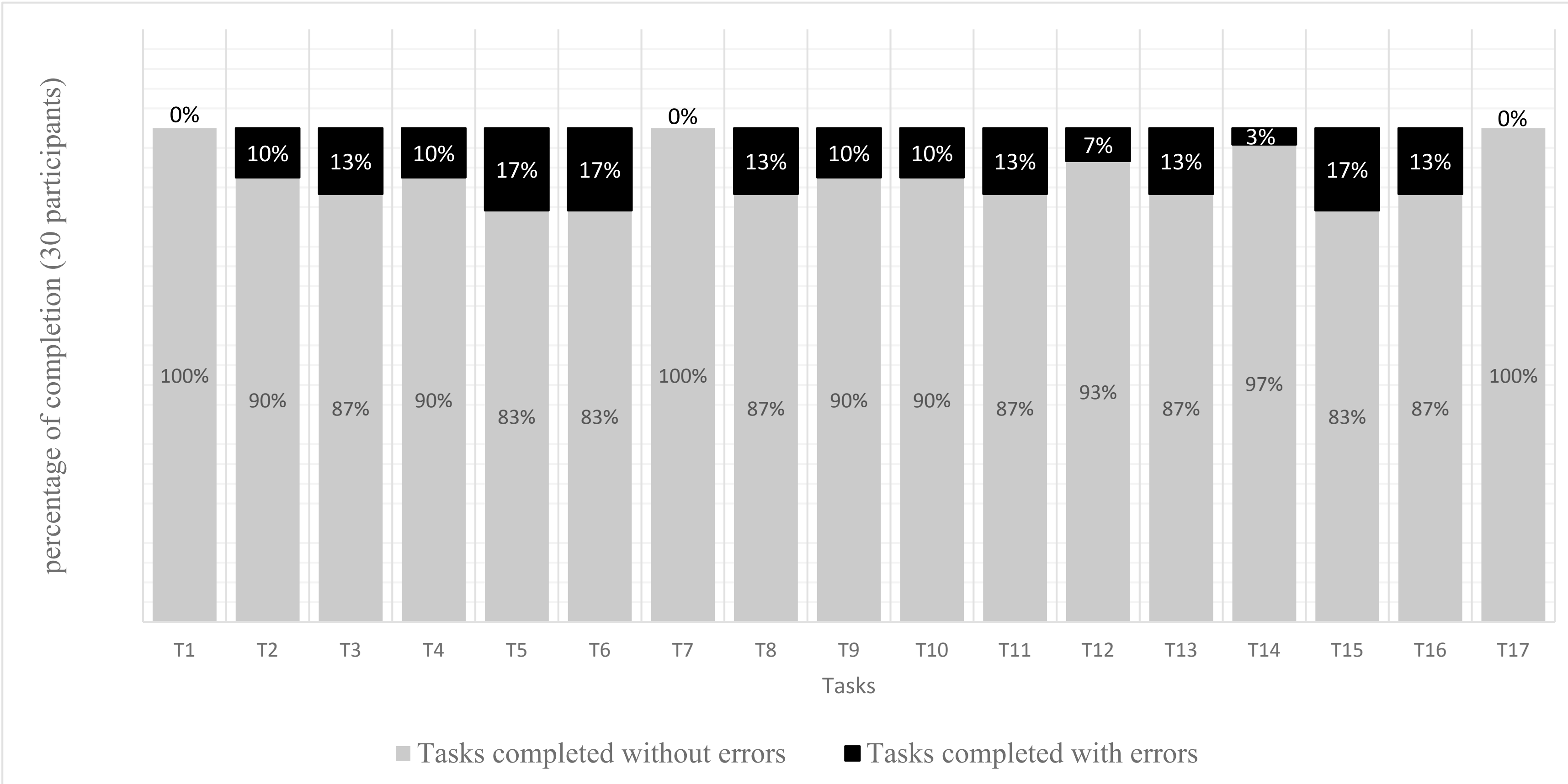


Figure 7-6 CBIM3R-FMS effectiveness chart

7.4 EVALUATION OF THE FEATURE-BASED TRACKING METHOD

To evaluate the accuracy of the feature-based tracking presented in Section 4.2.1, a testing scenario was developed to compare its results with a ground truth path marked on the floor. In addition, the results are compared with the tracking results using RTLS (UWB) based tracking. Based on the setting of the UWB system (i.e. Ubisense) discussed in Siddiqui (2014), the tracking results showed good location tracking for FM tasks (i.e. 15 cm).

For fair comparison, the two tracking data sets are used as row data without any corrections for data noise and errors caused by the instability of reading of the transmitted data. Similar to the main usability testing, this test was conducted at the same research lab on the 9th floor of the Engineering and Visual Arts Complex (EV) building of Concordia University. Figure 7-7 shows the lab layout where the test was conducted. As shown, there are four UWB sensors attached to the walls.

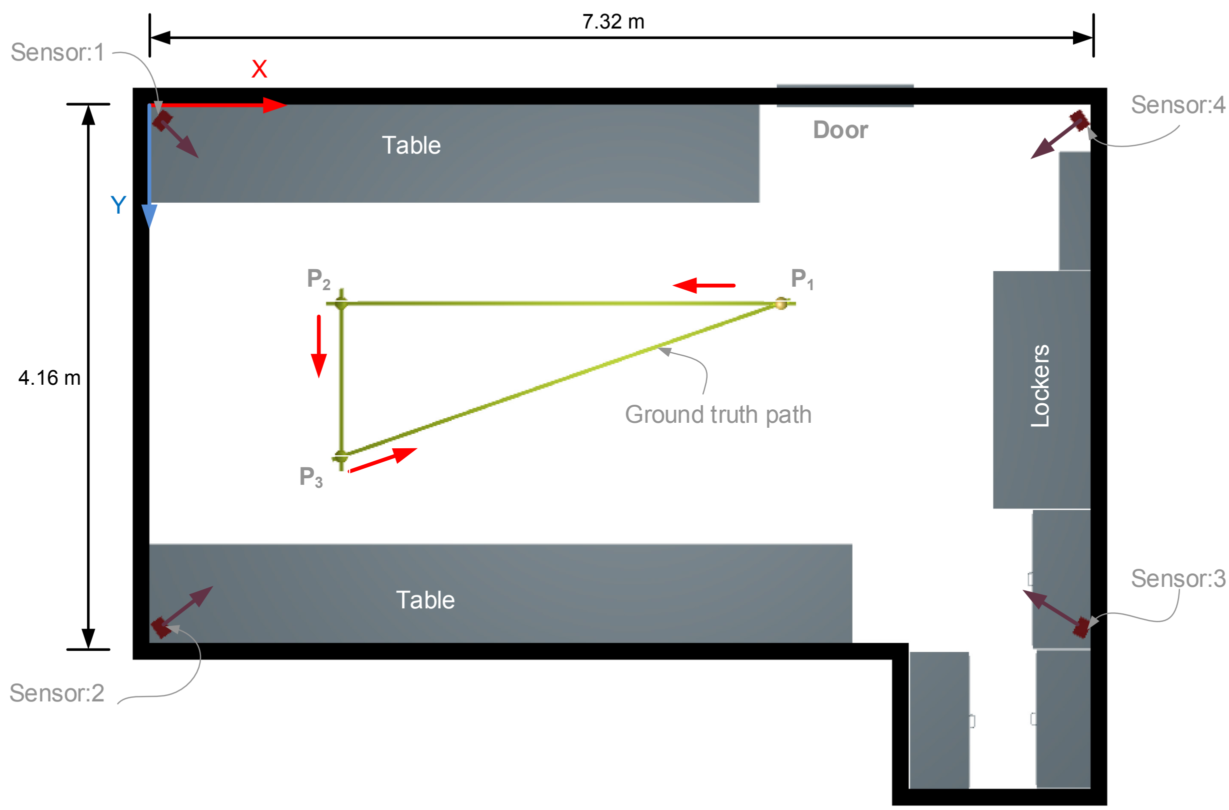


Figure 7-7 Testing area layout

As a testing scenario, the AR module user starts moving from point P_1 to P_2 and then from P_2 to P_3, and closing the triangle by moving from P_3 from P_1 in a steady movement. At an update rate of 30 FPS, the AR module starts recording AR camera pose (position and orientation). At the same update rate, the location data of the UWB tag are also recorded as shown in Figure 7-8. Both AR module and UWB tag data are collected with a timestamp for each reading to synchronize the two data readings.

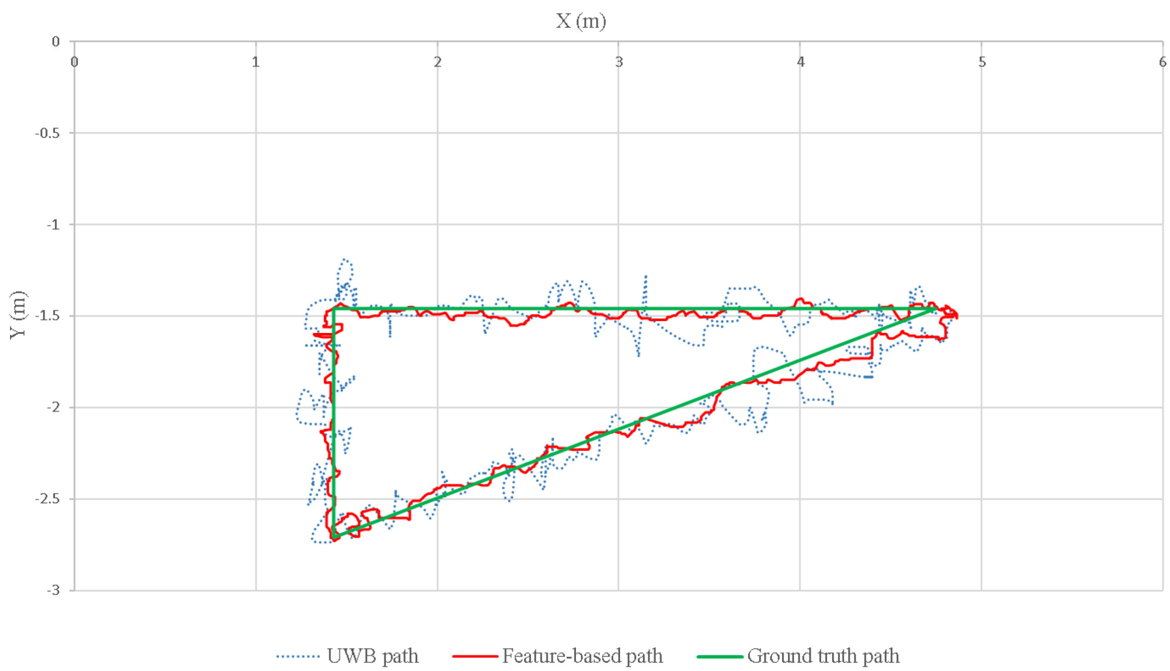


Figure 7-8 Tracking paths

Figure 7-9 shows one segment of the path starting from P_1 to P_2. The graph shows three paths: (1) the green path representing the ground truth; (2) the blue dotted path representing the path generated by the UWB tracking; and (3) the red path generated by the feature-based tracking method. As shown in Figure 7-10, the maximum error from the ground truth for the UWB tracking is 17.24 cm. On the other hand, the maximum error from the ground truth for the feature-based tracking is 15.52 cm.

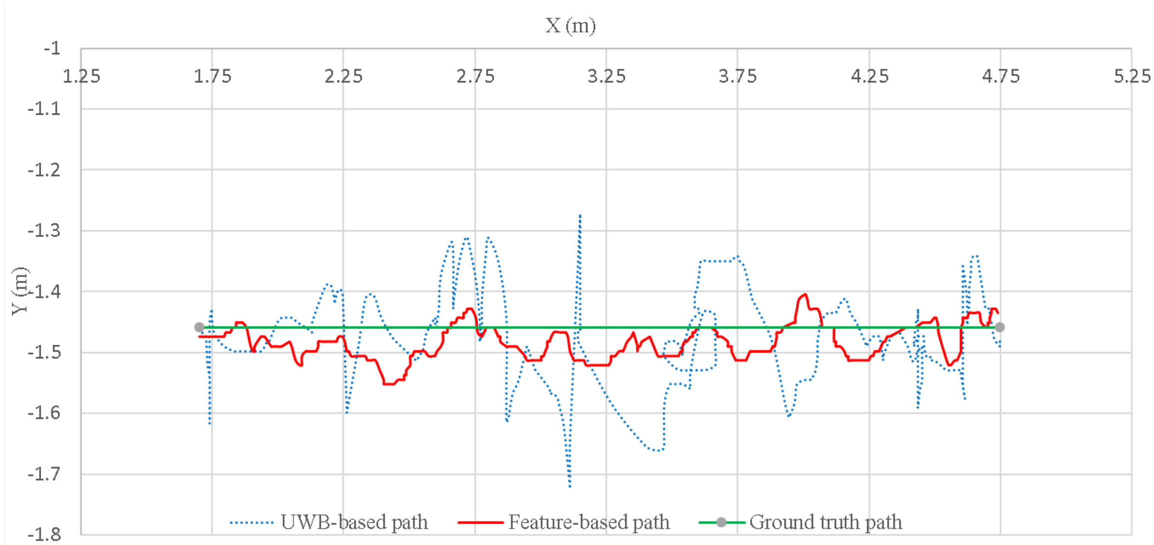


Figure 7-9 Tracking methods comparison graph

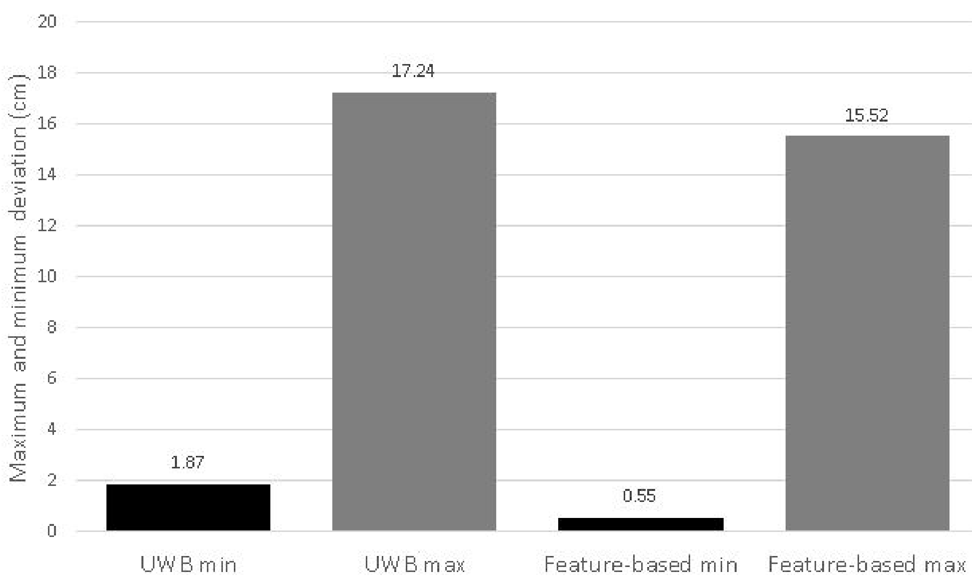


Figure 7-10 Maximum and minimum errors

7.5 SUMMARY AND CONCLUSIONS

This chapter discussed the validation of the framework presented in Chapter 3 and the methods presented in Chapters 4 and 5. To achieve this validation, it was necessary to fully implement the system architecture discussed in Section 3.6 as explained in Chapter 6. The validation has four major parts: (1) usability testing to quantify and analyze data related to the conducted questionnaire including user's satisfaction, time and errors analysis, (2) accuracy of remote marking and sketching, (3) system effectiveness, and (4) validating the tracking method by comparing it with a ground truth and RTLS (UWB).

The usability testing questionnaire is designed to consider all aspects of the proposed methods including tracking, visualization and IVC. The results discussed in Section 7.2.4 show that the participants found the AR module easy to use and provides visual support that can improve their task performance. The results also show that the filed tasks efficiency is improved by minimizing data entry time and errors. The field workers took much longer time (mean=11.88 sec.) to identify tagged tasks using non-collaborative approach compared with the IVC approach (1.82 sec.). That reduced the time by 85%. The number of errors occurred is also reduced by 62%. In addition, all participants agreed that being able to remotely mark a building element in a MR environment is useful to visually interact and communicate with a remote co-worker. The average error between the facility manager mark and the field worker mark is 0.31 cm. This error is considered acceptable for inspection and maintenance tasks where users not only can point on the building element, but they can also select a specific part of it. For example, the users can mark a part of a thermostat such as the screen, button, etc. On the other hand, the marking results show that the marking error from the ground truth in the AR module has larger distance 1.03 cm. In addition, ANOVA is used to determine whether there are any statistically significant differences between the means of using CBIM3R-FMS with and without IVC. The results show that there is a significant difference. Furthermore, the CBIM3R-FMS effectiveness validation results show that the overall integral effectiveness E is 90.20% with an effectiveness statistic error margin of ±1.8. This indicates that the system effectiveness is good according to ISO scale indicated in Section 7.3.

The accuracy of feature-based tracking is validated separately from the usability testing by comparing the tracking results with a ground truth path drawn on the floor and the results from an UWB tracking system installed in the same lab. The accuracy of tracking is acceptable compared with the UWB results, which is expensive to install and configure and also requires data noise filtering (Siddiqui 2014). The results show that UWB-based tracking has an average error of 14.73 cm, whereas the proposed tracking method has 8.56 cm. This makes the proposed tracking method a better and cheaper tracking solution for the AR module.

Participants have indicated that there are some aspects of the CBIM3R-FMS approach that can be improved. They recommended AR glasses for the AR module to allow the field worker to perform his/her tasks hands-free. Overall, they found CBIM3R-FMS, with its two modules, a promising tool for FM daily inspection and maintenance tasks.

CHAPTER 8 CONCLUSIONS, LIMITATIONS AND FUTURE WORK

8.1 SUMMARY

In the FM industry, day-to-day tasks require suitable methods to facilitate work orders and improve performance by better collaboration between the office and the field. As a rich facility model, BIM provides opportunities to support collaboration and to improve the efficiency of CMMSs by sharing building information between different applications/users throughout the lifecycle of the facility. However, manual retrieval of building element information can be challenging and time consuming for field workers during FM operations. As a visualization technique, MR can be used to improve the visual perception of the facility information by superimposing 3D virtual objects and BIM-based textual information on top of the view of real-world building objects.

This research discussed a general framework that integrates multisource facilities information, BIM models, and hybrid tracking in an MR setting to retrieve information based on time and the location of the field worker, visualize information related to inspection and maintenance operations, and support remote collaboration and visual communication between the field worker and the manager at the office. Furthermore, the research investigated an automated method to capture and record task-related data with respect to a georeferenced BIM model and share them directly with the remote office based on the field worker point of view in mobile situations. In addition, the research discussed visualization methods for improving the visual perception, which satisfy the needs of the facility manager at the office and the field worker with less visual and mental disturbance. These methods including the multilayer view, virtual hatch, and automatic MR scenes lighting are discussed in Chapter 4. Chapter 5 discussed the development of an effective method for interactive visual collaboration to improve FM field tasks. The IVC allows the field worker and the facility manager to remotely point and to sketch on each other views with high accuracy. In addition, sensory data (e.g., infrared thermography) provide an additional layer of information by augmenting the actual view of the field worker and supporting him/her in making effective decisions about existing and potential problems while communicating with the office in IVC mode.

A prototype system called CBIM3R-FMS with two modules is developed and discussed in Chapter 6. The field worker uses the AR module installed on his/her tablet. The manager at the office uses the IAV module installed on a desktop computer. The case study focused on Concordia University buildings. The usability testing of the CBIM3R-FMS is performed in two modes: non-collaborative mode, and IVC mode. Then, a questionnaire is designed and the results are discussed and analyzed using ANOVA in Chapter 7. The validation results include: (1) the users' satisfaction levels, (2) the effectiveness of CBIM3R-FMS, (3) the accuracy of the remote marking and sketching, and (4) the accuracy of the feature-based tracking.

8.2 CONTRIBUTIONS AND CONCLUSIONS

This research has the potential to improve FM field tasks. This research has made the following contributions to the body of knowledge:

(1) Developing the MR framework for facilities management which has field AR module and office IAV module. These two modules can be used independently or combined using interactive visual collaboration. With regard to this contribution the following conclusions can be drawn:

- The proposed method has a strong potential to improve FM field task operations using remote IVC between the field workers and facility managers at the office. The validation results show that the overall effectiveness of the proposed method is about 90.20%, which is considered good according to the ISO scale of system effectiveness.

- The field and the office tasks can be performed independently with the ability to consult and coordinate at any time without misinterpretation of the task related data.

- Filed tasks efficiency is improved by minimizing data entry time and errors. The validation results show that field workers took longer time (mean=11.88 sec.) to identify tagged tasks when using the non-collaborative approach compared with the IVC approach (mean=1.82 sec.). That reduced the time by 85%. The number of errors is also reduced by 62%. Therefore, the productivity of the FM field worker and office manager can be considerably improved.

(2) Developing visualization methods for MR including virtual hatch and multilayer views to enhance visual depth and context perception. Based on the case study that demonstrated the feasibility of the proposed visualization methods, the following conclusions are drawn:

- The depth perception in the AR module is improved by introducing the virtual hatch, which provides better perception to the viewer in terms of the order of the 3D elements in the AR view. The validation results show that all the usability test participants unanimously agreed that the virtual hatch improved their visual depth perception.

- FM field and office tasks' visualization is enhanced by introducing the multilayer view method that helps in identifying when, what, and how to visualize task data to different stakeholders without causing any confusion and with less physical and metal loads. The validation results show that the mental load when using the AR module is low (mean=1.37) and the physical load is also low (mean=1.77). The users who used the IAV module agreed that the module reduces the mental load (mean=1.83) and requires between low and moderate physical load (mean=2.33).

- Sharing remote visual information has improved the context awareness of the facility manager. This is achieved by sharing the AR module camera and IR camera views as layers of remote information. The validation results show that all participants unanimously agreed that sharing remote sensory data as a multilayer view provided more informative visual information.

(3) Developing methods for AR and IAV modeling including BIM-based data integration and customization suitable for each MR module. The following conclusions are drawn:

- Visualizing multilevel facilities data increased the scalability of the system to cover other phases of the facility lifecycle.

- Customizing BIM data satisfied the needs for the field workers using the AR module and the facility managers using the IAV module. The BIM optimization method helped in reducing the number of triangles and vertices by 79% and 56%, respectively. This reduces the need of the computation resources in AR module.

(4) Developing mobile indoor hybrid tracking method for the AR module. This contribution has the following conclusion:

- Besides the low cost of the hybrid tracking, the validation results show that the tracking errors are from 0.55 to 15.52 cm compared with the tracking method using expensive RTLSs (i.e. UWB) where the errors range from 1.87 to 17.24 cm.

- The hybrid tracking method was able to solve the issue of temporal loss of tracking caused by undetected registered features when the AR module user navigates in space. Merging CV-based and sensor-based tracking methods improved the tracking for the mobile MR FM application.

(5) Full implementation and testing for the proposed methods. The usability testing results show that the AR module users agreed that they are satisfied with the overall easiness of the module (mean=1.77) and the time it took them to complete the assigned tasks (mean=1.77). The mean overall users' satisfaction levels of the IAV module is 2.17 for the easiness of use and 2.20 for the completion time.

8.3 RESEARCH LIMITATIONS AND FUTURE WORK

While this research has successfully achieved its objectives, the following limitations still remain to be addressed in the future:

(1) The core part of the hybrid tracking is the feature-based tracking, which requires unique, well-distributed features to be used as targets. In indoor spaces, having enough features can be challenging. This limitation can be addressed in the future by investigating the use of 360º FoV cameras, which are able to capture more features (Côté et al. 2013).
(2) For the maintenance phase, using the tablet-based AR module is safer than using AR glasses. However, field workers need to work with their hands. For the future studies, it is recommended to investigate methods for projecting the AR module contents on surrounding surfaces instead of seeing them through a tablet or AR glasses. The challenge

is the interaction with the AR module functionalities. MIT's SixthSense technology can be considered for integration with the AR module (Mistry and Maes 2009).

(3) Considering the scalability of the proposed framework, more issues related to outdoor feature-based tracking, such as changes in light conditions and reflective surfaces, should be considered.

(4) Visualization issues, including moving object occlusion in AR, should be investigated. In addition, augmenting sensory data, such as thermometers and light sensors, can be investigated.

REFERENCES

Anyplace. (2018). "A free and open indoor navigation service with superb accuracy." Retrieved on 05/06/2018 from: <http://anyplace.cs.ucy.ac.cy>.

Apache. (2018). "Xerces java parser." Retrieved on 02/06/2018 from: <https://xerces.apache.org/xerces-j/>.

ARTag. (2009). "ARTag applications for windows." Retrieved on 02/03/2018 from: <https://web.archive.org/web/20120814082107/http://www.artag.net/>.

Asen, Y. (2012). "Building information modeling based integration and visualization for facilities management." *Master thesis*, Concordia University, Montreal, QC, Canada.

Atmel. (2017). "ATR0635 (ATMEL)." Retrieved on 05/07/2018 from: <http://doc.chipfind.ru/atmel/atr0635.htm>.

Autodesk360. (2018). "A360: collaboration for design teams." Retrieved on 03/15/2018 from: <https://a360.autodesk.com/>.

Azuma, R.T. (1997). "A survey of augmented reality." *Presence: Teleoperators & Virtual Environments,* 6(4), pp. 355-385.

Barnes, J., Rizos, C., Wang, J., Small, D., Voigt, G. and Gambale, N. (2003). "Locata: the positioning technology of the future." *Proceedings of the 6th International Symposium on Satellite Navigation Technology Including Mobile Positioning & Location Services* 2003.

Becerik-Gerber, B. Jazizadeh, F. Li, N. and Calis, G. (2011). "Application areas and data requirements for BIM-enabled facilities management." *Journal of Construction Engineering and Management,* 138(3), pp. 431-442.

Beetz, J. and Borrmann, A. (2018). "Benefits and limitations of linked data approaches for road modeling and data exchange." *Proceedings of Workshop of the European Group for Intelligent Computing in Engineering* 2018, Springer, pp. 245-261.

Behzadan, A.H. and Kamat, V.R. (2009). "Interactive augmented reality visualization for improved damage prevention and maintenance of underground infrastructure." *Proceedings of Construction Research Congress 2009: Building a Sustainable Future*, pp. 1214-1222.

Behzadan, A.H. and Kamat, V.R. (2007). "Georeferenced registration of construction graphics in mobile outdoor augmented reality." *Journal of Computing in Civil Engineering,* 21(4), pp. 247-258.

Behzadan, A.H., Menassa, C.C. and Kamat, V.R. (2018). “Georeferenced augmented reality for discovery-based learning in civil engineering." *Transforming Engineering Education: Innovative Computer-Mediated Learning Technologies*, pp. 199-228.

BIFM. (2016). "Facilities management introduction." Retrieved on 12/06/2016 from: <http://www.bifm.org.uk>.

Bluebeam. (2017). "Bluebeam revu is aniOS." Retrieved on 12/23/2017 from: <https://www.bluebeam.com/solutions/revu-ipad>.

Bluescape. (2018). "Collaborative workspace and virtual workspace." Retrieved on 06/12/2019 from: <https://bluescape.com/>.

Bosché, F., Tingdahl, D., Carozza, L. and Van Gool, L. (2012). "Markerless vision-based augmented reality for enhanced project visualization." *Proceedings of ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction* 2012, Vilnius Gediminas Technical University, Department of Construction Economics & Property, 29, pp. 1-9.

BuildingSMART. (2018). "International home of open BIM." Retrieved on 01/02/2018 from: <https://www.buildingsmart.org/>.

Carboni, D. Manchinu, A. Marotto, V. Piras, A. and Serra, A. (2015). "Infrastructure-free indoor navigation: a case study." *Journal of Location Based Services,* 9(1), pp. 33-54.

Chen, J. and Clarke, K.C. (2017). "Modeling standards and file formats for indoor mapping." *Proceedings of the 3rd International Conference on Geographical Information Systems Theory, Applications and Management (GISTAM 2017)* 2017, pp. 268-275.

Cho, Y.K. Youn, J.H. and Martinez, D. (2010). "Error modeling for an untethered ultra-wideband system for construction indoor asset tracking." *Automation in Construction,* 19(1), pp. 43-54.

Chu, M. Matthews, J. and Love, P.E. (2018). "Integrating mobile building information modelling and augmented reality systems: an experimental study." *Automation in Construction,* 85, pp. 305-316.

CityGML. (2018). "CityGML and what data can be stored in it." Retrieved on 02/23/2018 from: <https://www.citygml.org/about/>.

Collins, T., Pizarro, D., Bartoli, A., Canis, M. and Bourdel, N. (2014). "Computer-assisted laparoscopic myomectomy by augmenting the uterus with pre-operative MRI data." *Proceedings of Mixed and Augmented Reality (ISMAR), 2014 IEEE International Symposium on 2014, IEEE*, pp. 243-248.

Côté, S., Barnard, J., Snyder, R. and Gervais, R. (2013). "Offline spatial panoramic video augmentation for visual communication in the AEC industry." *Proceedings of 13th International Conference on Construction Applications of Virtual Reality (CONVR 2013)* 2013, pp. 82-89.

Côté, S., Letourneau, I. and Marcoux-Ouellet, J. (2014). "[Poster] Augmentation of live excavation work for subsurface utilities engineering." *Proceedings of Mixed and Augmented Reality (ISMAR), 2014 IEEE International Symposium on* 2014, IEEE, pp. 259-260.

Côté, S., Trudel, P., Desbiens, M., Giguère, M. and Snyder, R. (2013). "Live mobile panoramic high accuracy augmented reality for engineering and construction." 2013, pp. 1-10.

Dai, F. Lu, M. and Kamat, V.R. (2010). "Analytical approach to augmenting site photos with 3D graphics of underground infrastructure in construction engineering applications." *Journal of Computing in Civil Engineering,* 25(1), pp. 66-74.

Datcu, D., Cidota, M., Lukosch, H. and Lukosch, S. (2014). "On the usability of augmented reality for information exchange in teams from the security domain." *Proceedings of Intelligence and Security Informatics Conference (JISIC), 2014 IEEE Joint* 2014, IEEE, pp. 160-167.

Deak, G. Curran, K. and Condell, J. (2012). "A survey of active and passive indoor localisation systems." *Computer Communications,* 35(16), pp. 1939-1954.

Deng, Z. Li, H. Tam, C. Shen, Q. and Love, P. (2001). "An application of the Internet-based project management system." *Automation in Construction,* 10(2), pp. 239-246.

Deng, Y. Cheng, J.C. and Anumba, C. (2016). "Mapping between BIM and 3D GIS in different levels of detail using schema mediation and instance comparison." *Automation in Construction,* 67, pp. 1-21.

Dong, S. Behzadan, A.H. Chen, F. and Kamat, V.R. (2013). "Collaborative visualization of engineering processes using tabletop augmented reality." *Advances in Engineering Software,* 55, pp. 45-55.

Dong, S., Feng, C. and Kamat, V.R. (2011). Occlusion handling method for ubiquitous augmented reality using reality capture technology and GLSL." *Computing in Civil Engineering 2011*, pp. 494-503.

Drossis, G. and Stephanidis, C. (2018). "Enriching mixed reality systems with mobile applications." *Proceedings of International Conference on Human-Computer Interaction 2018*, Springer, pp. 237-244.

Du, J. Zou, Z. Shi, Y. and Zhao, D. (2018). "Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making." *Automation in Construction,* 85, pp. 51-64.

Dunston, P.S. (2008). "Identification of application areas for augmented reality in industrial construction based on technology suitability." *Automation in Construction,* 17(7), pp. 882-894.

East, W. (2007). "Construction operations building information exchange (Cobie): Requirements definition and pilot implementation standard (No. ERDC/CERL TR-07-30)." *U.S. Army Engineer Research and Development Center, champaign, IL, construction engineering research lab.*

Eastman, C., Teicholz, P., Sacks, R. and Liston, K. (2011). "*BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors.*" John Wiley & Sons.

El Ammari, K. (2006). "Visualization, data sharing and interoperability issues in model-based facilities management systems." *Master thesis*, Concordia University, Montreal, QC, Canada.

El Ammari, K. and Hammad, A., (2014). "Collaborative BIM-based markerless mixed reality framework for facilities maintenance." *In Computing in Civil and Building Engineering*, pp. 657-664.

Feick, M., Tang, A. and Bateman, S. (2018). "Mixed-reality for object-focused remote collaboration." *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology Adjunct Proceedings 2018*, ACM, pp. 63-65.

FlirOne. (2018). "Thermal imaging cameras for your Smartphone." Retrieved on 12/01/2018 from: <https://www.flir.ca/flir-one/>.

Gallaher, M.P., O'Connor, A.C., Dettbarn, J.L. and Gilday, L.T. (2004). "Cost analysis of inadequate interoperability in the US capital facilities industry." *National Institute of Standards and Technology (NIST)*, GCR 04-867, Retrieved on 21/03/2017 from: < https://www.lagospm.com/03-benefits/articles/NIST.pdf>.

Gauglitz, S., Nuernberger, B., Turk, M. and Höllerer, T. (2014). "In touch with the remote world: remote collaboration with augmented reality drawings and virtual navigation." *Proceedings of the 20th ACM Symposium on Virtual Reality Software and Technology 2014*, ACM, pp. 197-205.

Gelder, J., Tebbit, J., Wiggett, D., and Mordue, S. (2013). "BIM for the terrified: a guide for manufacturers." *Construction Products Association*, Retrieved on 06/04/2017 from: <https://www.nationalbimlibrary.com/content/pdfs/bim_for_the_terrified.pdf>.

Georgel, P., Schroeder, P., Benhimane, S., Hinterstoisser, S., Appel, M. and Navab, N. (2007). "An industrial augmented reality solution for discrepancy check." *Proceedings of the 6th IEEE and ACM International Symposium on Mixed and Augmented Reality* 2007, IEEE Computer Society, pp. 1-4.

Georgiou, K., Constambeys, T., Laoudias, C., Petrou, L., Chatzimilioudis, G. and Zeinalipour-Yazti, D. (2015). "Anyplace: A crowdsourced indoor information service." *Proceedings of Mobile Data Management (MDM), 2015 16th IEEE International Conference on* 2015, IEEE, pp. 291-294.

Ghavami, M., Michael, L. and Kohno, R. (2007). "Ultra wideband signals and systems in communication engineering." John Wiley & Sons.

Gheisari, M. and Irizarry, J. (2016). "Investigating human and technological requirements for successful implementation of a BIM-based mobile augmented reality environment in facility management practices." *Facilities,* 34, pp. 69-84.

Giretti, A. Carbonari, A. Naticchia, B. and DeGrassi, M. (2009). "Design and first development of an automated real-time safety management system for construction sites." *Journal of Civil Engineering and Management,* 15(4), pp. 325-336.

Gjøsæter, T., (2012). "A taxonomy of handheld augmented reality applications." *Proceedings of 4th International Conference on Intelligent Human Computer Interaction (IHCI)*, IEEE, pp. 1-6.

Gröger, G. and Plümer, L. (2012). "CityGML–Interoperable semantic 3D city models." *ISPRS Journal of Photogrammetry and Remote Sensing,* 71, pp. 12-33.

Grundhöfer, A., Seeger, M., Hantsch, F. and Bimber, O. (2007). "Dynamic adaptation of projected imperceptible codes." *Proceedings of Proceedings of the 2007 6th IEEE and ACM International Symposium on Mixed and Augmented Reality 2007, IEEE Computer Society*, pp. 1-10.

Hagan, S. (2015). "iFM: integrated facility management." *Journal of the National Institute of Building Sciences (JNIBS)*, 1(2), pp. 28-30.

Hammad, A., Khabeer, B., Mozaffari, E., Devarakonda, P. and Bauchkar, P. (2005). "Augmented reality interaction model for mobile infrastructure management systems." *Proceedings of 1st CSCE Specialty Conference on Infrastructure Technologies, Management and Policy 2005*, pp. 1-10.

Hammad, A. Wang, H. and Mudur, S.P. (2009). "Distributed augmented reality for visualizing collaborative construction tasks." *Journal of Computing in Civil Engineering,* 23(6), pp. 418-427.

Han, J. (2018). "Introduction to computer graphics with OpenGL ES." *CRC Press*.

Haouchine, N., Dequidt, J., Peterlik, I., Kerrien, E., Berger, M. and Cotin, S. (2013). "Image-guided simulation of heterogeneous tissue deformation for augmented reality during hepatic surgery." *Proceedings of Mixed and Augmented Reality (ISMAR), 2013 IEEE International Symposium on 2013, IEEE*, pp. 199-208.

Harris, C. and Stephens, M. (1988). "A combined corner and edge detector." *Proceedings of Alvey vision conference* 1988, Citeseer, pp. 10-5244.

Hart, S.G. (2006). "NASA-task load index (NASA-TLX); 20 years later." *Proceedings of the human factors and ergonomics society annual meeting* 2006, Sage Publications Sage CA: Los Angeles, CA, pp. 904-908.

Hoffmann, M., Meisen, T. and Jeschke, S. (2016). "Shifting virtual reality education to the next level–Experiencing remote laboratories through mixed reality." *Automation, Communication and Cybernetics in Science and Engineering 2015/2016,* Springer, Cham., pp. 293-307.

Hou, L. Wang, X. and Truijens, M. (2013). "Using augmented reality to facilitate piping assembly: an experiment-based evaluation." *Journal of Computing in Civil Engineering,* 29(1).

Huang, W., Alem, L. and Tecchia, F. (2013). "HandsIn3D: supporting remote guidance with immersive virtual environments." *Proceedings of IFIP Conference on Human-Computer Interaction* 2013, Springer, pp. 70-77.

IBM (2016). "IBM Maximo: BIM360 viewer integration." Retrieved on 01/015/2016 from: <https://www.ibm.com/products/maximo/add-ons>.

IFMA. (2011). "International facility management association." Retrieved on 12/11/2017 from: <www.ifma.org>.

InfraWorks. (2018). "How InfraWorks works with other Autodesk software." Retrieved on 03/02/2018 from: <http://www.autodesk.com/products/infraworks-360/overview>.

Irizarry, J. Gheisari, M. Williams, G. and Walker, B.N. (2013). "InfoSPOT: A mobile augmented reality method for accessing building information through a situation awareness approach." *Automation in Construction,* 33, pp. 11-23.

Ismail, A.W. and Sunar, M.S. (2009). "Collaborative augmented reality: multi-user interaction in urban simulation." *Proceedings of International Visual Informatics Conference 2009*, Springer, pp. 382-391.

ISO (1998). "ISO 9241-11:1998, Ergonomic requirements for office work with visual display terminals (VDTs) - Part 11: Guidance on usability." Retrieved on 05/04/2018 from: <https://www.iso.org/obp/ui/#iso:std:iso:9241:-11:ed-1:v1:en>.

Izkara, J.L., Pérez, J., Basogain, X. and Borro, D. (2007). "Mobile augmented reality, an advanced tool for the construction sector." *Proceedings of the 24th W78 conference, Maribor, Slovenia* 2007, Citeseer, pp. 190-202.

Kang, T.W. and Hong, C.H. (2015). "A study on software architecture for effective BIM/GIS-based facility management data integration." *Automation in Construction,* 54, pp. 25-38.

Kestle, L. (2009). "Remote site design management." *Doctoral dissertation*, University of Canterbury, New Zealand.

Khan, D. Ullah, S. Yan, D. Rabbi, I. Richard, P. Hoang, T. Billinghurst, M. and Zhang, X. (2018). "Robust tracking through the design of high quality fiducial markers: An optimization tool for ARToolKit." *IEEE access,* 6, pp. 22421-22433.

Kim, K. Billinghurst, M. Bruder, G. Duh, H.B. and Welch, G.F. (2018). "Revisiting Trends in Augmented Reality Research: A Review of the 2nd Decade of ISMAR (2008–2017)." *IEEE Transactions on Visualization and Computer Graphics*, 24(11), pp. 2947-2962.

Koch, C., Neges, M., König, M. and Abramovici, M. (2012). "BIM-based augmented reality for facility maintenance using natural markers." *Proceedings of the EG-ICE International Workshop on Intelligent Computing in Engineering 2012*, Citeseer.

LaMarca, A., Chawathe, Y., Consolvo, S., Hightower, J., Smith, I., Scott, J., Sohn, T., Howard, J., Hughes, J. and Potter, F. (2005). "Place lab: Device positioning using radio beacons in the wild." *Proceedings of International Conference on Pervasive Computing 2005*, Springer, pp. 116-133.

Leap motion (2018). "Leap motion documentation." Retrieved on 15/01/2018 from: <https://developer.leapmotion.com/documentation/>.

Lee, W.H., Sengupta, K. and Sharma, R. (2003). "Augmented reality with occlusion rendering using background-foreground segmentation and trifocal tensors." *Proceedings of Multimedia and Expo, 2003. ICME'03. Proceedings. 2003 International Conference on 2003, IEEE*, 2, pp. II-93. Baltimore, MD, USA.

Lewis, J.R. (1995). "IBM computer usability satisfaction questionnaires: psychometric evaluation and instructions for use." *International Journal of Human‐Computer Interaction,* 7(1), pp. 57-78.

Li, J., Laganiere, R. and Roth, G. (2004). "Online estimation of trifocal tensors for augmenting live video." *Proceedings of Proceedings of the 3rd IEEE/ACM International Symposium on Mixed and Augmented Reality* 2004, IEEE Computer Society, pp. 182-190.

Lincoln, P., Welch, G., Nashel, A., Ilie, A., State, A. and Fuchs, H. (2009). "Animatronic shader lamps avatars." *Proceedings of 2009 8th IEEE International Symposium on Mixed and Augmented Reality 2009, IEEE*, pp. 27-33.

Liu, F. and Seipel, S. (2018). "Precision study on augmented reality-based visual guidance for facility management tasks." *Automation in Construction,* 90, pp. 79-90.

Liu, H. Darabi, H. Banerjee, P. and Liu, J. (2007). "Survey of wireless indoor positioning techniques and systems." *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews),* 37(6), pp. 1067-1080.

Lowe, D.G. (2004). "Distinctive image features from scale-invariant keypoints." *International journal of computer vision,* 60(2), pp. 91-110.

Lukosch, S. (2015). "Towards virtual co-location and telepresence based on augmented reality." *Semantic Scholar*.

Madritsch, T. and May, M. (2009). "Successful IT implementation in facility management." *Facilities,* 27(11/12), pp. 429-444.

Maimone, A. and Fuchs, H. (2011). "Encumbrance-free telepresence system with real-time 3D capture and display using commodity depth cameras." *Proceedings of Mixed and augmented reality (ISMAR), 2011 10th IEEE international symposium on 2011, IEEE*, pp. 137-146.

MaintenanceConnection. (2017). "Maintenance Connection - computerized maintenance management software." Retrieved on 01/06/2017 from: <www.maintenanceconnection.com>.

Microsoft. (2018). "Microsoft Hololens." Retrieved on 02/25/2018 from: <https://www.microsoft.com/microsoft-hololens/en-us>.

Milgram, P. and Colquhoun, H. (1999). "A taxonomy of real and virtual world display integration." *Mixed reality: Merging real and virtual worlds,* 1, pp. 1-26.

Mistry, P. and Maes, P. (2009). "SixthSense: a wearable gestural interface." *Proceedings of ACM SIGGRAPH ASIA 2009 Sketches* 2009, ACM, pp. 11.

Miyamoto, A. Konno, M. and Rissanen, T. (2006). "VR-based education system for inspection of concrete bridges." *Computers and concrete,* 3(1), pp. 29-42.

Morton, J. (2013). "Three reasons you need a thermal imager." *Building smarter facilities management*, Retrieved on 03/25/2018 from: <https://www.buildings.com/article-details/articleid/15448/title/three-reasons-you-need-a-thermal-imager/viewall/true>.

Motamedi, A. Hammad, A. and Asen, Y. (2014). "Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management." *Automation in Construction*, 43, pp. 73-83.

Motamedi, A. Soltani, M.M. and Hammad, A. (2013). "Localization of RFID-equipped assets during the operation phase of facilities." *Advanced Engineering Informatics*, 27(4), pp. 566-579.

Neges, M. Koch, C. König, M. and Abramovici, M. (2017). "Combining visual natural markers and IMU for improved AR based indoor navigation." *Advanced Engineering Informatics*, 31, pp. 18-31.

Netfacilities. (2018). "Netfacilities CMMS solution." Retrieved on 05/06/2018 from: <https://www.netfacilities.com>.

NIBS. (2018). "Whole building' design guide: Building Information Modeling (BIM)." Retrieved on 02/05/2018 from: <https://www.wbdg.org/ffc/army-coe/cadbim-technology-center/bim-cim>.

Nizam, R.S. and Zhang, C. (2017). "A Review of industry foundation class (IFC) based data exchange model." *Integrated Building Information Modelling*, pp. 158-180.

Nor, N., Mohammed, A., and Alias, B. (2014). "Facility management history and evolution." *International Journal of Facility Management*, 5(1).

Normand, J., Servieres, M. and Moreau, G. (2012). "A typology of augmented reality applications based on their tracking requirements." *Proceedings of Location Awareness for Mixed and Dual Reality. LAMDa workshop. Lisbon, Portugal* 2012.

Oculus. (2018). "Virtual reality headset review." Retrieved on 01/03/2018 from: <https://www.oculus.com/>.

Oda, O., Sukan, M., Feiner, S. and Tversky, B. (2013). "Poster: 3D referencing for remote task assistance in augmented reality." *Proceedings of 3D User Interfaces (3DUI), 2013 IEEE Symposium on* 2013, IEEE, pp. 179-180.

Papapostolou, A. and Chaouchi, H. (2011). "RFID-assisted indoor localization and the impact of interference on its performance." *Journal of Network and Computer Applications,* 34(3), pp. 902-913.

Park, C. Lee, D. Kwon, O. and Wang, X. (2013). "A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template." *Automation in Construction,* 33, pp. 61-71.

Piirainen, K.A. Kolfschoten, G.L. and Lukosch, S. (2012). "The joint struggle of complex engineering: A study of the challenges of collaborative design." *International Journal of Information Technology & Decision Making,* 11(06), pp. 1087-1125.

Prandi, F. Devigili, F. Soave, M. Di Staso, U. and De Amicis, R. (2015). "3D web visualization of huge CityGML models." *International Archives of the Photogrammetry,* *Remote Sensing and Spatial Information Sciences,* 40, pp. 601-605, La Grande Motte, France.

Rankohi, S. and Waugh, L. (2013). "Review and analysis of augmented reality literature for construction industry." Visualization in Engineering, 1:9.

Revit. (2018). "Building Information Modeling applications." Retrieved on 05/22/2018 from: <http://www.autodesk.com/products/revit-family/overview>.

Revizto. (2018). "Revizto: real-time issue tracking software for architecture, engineering and construction with a focus on collaboration and BIM project coordination." Retrieved on 02/23/2018 from: <https://revizto.com/en/>.

Roberts, G.W., Evans, A., Dodson, A., Denby, B., Cooper, S. and Hollands, R. (2002). "The use of augmented reality, GPS and INS for subsurface data visualization." *Proceedings of FIG XXII International Congress* 2002, pp. 1-12.

Rodriguez, A., Zhang, C. and Hammad, A. (2010). "Feasibility of location tracking of construction resources using UWB for better productivity and safety." *Proceedings of The Conference on Computing in Civil and Building Engineering 2010*. Nottingham.

Rodriguez, R.M. Aguilar, R. Uceda, S. and Castañeda, B. (2018). "3D pose estimation oriented to the initialization of an augmented reality system applied to cultural heritage." *Digital Cultural Heritage*, pp. 277-288.

Sabol, L. (2013). "BIM technology for FM." *BIM for Facility Managers, 1st Edition, New Jersey: John Wiley & Sons*, pp. 17-45.

Samsung. (2017). "Samsung Gear VR." Retrieved on 12/21/2018 from: <https://www.samsung.com/ca/wearables/gear-vr-r325/>.

Schall, G., (2011). "Mobile augmented reality for human scale interaction with geospatial models: The benefit for industrial applications." *Doctoral dissertation*, Graz University of Technology.

Schall, G., Schmalstieg, D., and Junghanns, S. (2010). "VIDENTE-3D visualization of underground infrastructure using handheld augmented reality." *GeoHydroinformatics: Integrating GIS and Water Engineering*, CRC Press, pp. 207-219.

Schley, M. (2012). "BIM for facility management managing for the building life cycle." *FM: Systems*, Retrieved on 03/26/2016 from: < http://www.fmsystems.com/>.

Schon, S. and Bielenberg, O. (2008). "On the capability of high sensitivity GPS for precise indoor positioning." *Proceedings of Positioning, Navigation and Communication, WPNC, 5th Workshop on* 2008, IEEE, pp. 121-127.

Schwabe, K., Dichtl, M., König, M. and Koch, C. (2018). "COBie: a specification for the construction operations building information exchange." *Building Information Modeling*, Springer, pp. 167-180.

Shirazi, A. and Behzadan, A.H. (2015). "Content delivery using augmented reality to enhance students' performance in a building design and assembly project." *Advances in Engineering Education,* 4(3), p. n3.

Sidawi, B. and Alsudairi, A. (2014). "The potentials of and barriers to the utilization of advanced computer systems in remote construction projects: case of the Kingdom of Saudi Arabia." *Visualization in Engineering,* 2(1), p. 3-14.

Siddiqui, H. (2014). "UWB RTLS for construction equipment localization: experimental performance analysis and fusion with video data." *Master thesis*, Concordia University, Montreal, QC, Canada.

Sjogren, J. and Kvarsvik, K. (2007). "BuildingSMART standards: Information and demonstration." *Proceedings of EUREKABUILD Workshop 2007.*

Sokolov, I. and Crosby, J. (2011). "Utilizing gbXML with AECOsim building designer and speedikon." Retrieved on 04/15/2017 from: <https://www.bentley.com/-/media/2047CE42508743F2874D250CDB48BE3F/>.

Sørensen, J.B. and Svidt, K. (2017). "BIM-based Multiuser Collaborative Virtual Environments for end user involvement." *Proceedings of 35th Annual International Conference of eCAADe–Educational and research in Computer Aided Architectural Design in EuropeEducation and research in Computer Aided Architectural Design in Europe* 2017, eCAADe, pp. 111-118.

Sun, C. Jiang, S. Skibniewski, M.J. Man, Q. and Shen, L. (2017). "A literature review of the factors limiting the application of BIM in the construction industry." *Technological and Economic Development of Economy,* 23(5), pp. 764-779.

Svetel, I. Jarić, M. and Budimir, N. (2014). "BIM: Promises and reality." *Spatium,* (32), pp. 34-38.

Syafar, F. Gao, J. and Du, J.T. (2015). "The success implementation factors for mobile collaboration technology in asset maintenance." *Journal of Mobile Technologies, Knowledge and Society,* 2015 (2015), Article ID 459687, DOI: 10.5171/2015.459687.

Teicholz, P. (2013). "BIM for facility managers." *IFMA Foundation*, John Wiley & Sons Inc., Hoboken, New Jersey.

Teizer, J., Lao, D. and Sofer, M. (2007). "Rapid automated monitoring of construction site activities using ultra-wideband." *Proceedings of the 24th International Symposium on Automation and Robotics in Construction, Kochi, Kerala, India* 2007, pp. 19-21.

Thiel, A., Uerikon, H. and Favey, E. (2007). "U-blox" Patent No. US 7,170,445 B2., USA.

Thomas, S. and O'Hanlon, T. (2011) "CMMS best practices report." *U.S.A: Reliabilityweb*.

Turner, J.R. and Thayer, J. (2001). "Introduction to analysis of variance: design, analysis & interpretation." *Sage Publications*, London.

Underwood, J. and Isikdag, U. (2011). "Emerging technologies for BIM 2.0." *Construction Innovation,* 11(3), pp. 252-258.

Unity3D. (2018). "Unity3D game engine." Retrieved on 04/14/2018 from: <http://unity3d.com>.

Van Diggelen, F. (2002). "Indoor GPS theory & implementation." *Proceedings of Position Location and Navigation Symposium, IEEE* 2002, IEEE, pp. 240-247.

Ville de Montréal. (2017). "The digital model of southwest and Ville-Marie - CityGML LOD2 buildings with textures." Retrieved on 05/10/2017 from: <http://donnees.ville.montreal.qc.ca/dataset/maquette-numerique-batiments-citygml-lod2-avec-textures>.

Vuforia. (2018). "Natural features and image ratings." Retrieved on 01/03/2018 from: <https://library.vuforia.com/articles/Solution/Optimizing-Target-Detection-and-Tracking-Stability#Natural-Features-and-Image-Ratings>.

Vuforia SDK. (2018). "How to install the Vuforia SDK Unity3D extension." Retrieved on 09/12/2017 from: <https://library.vuforia.com/articles/Solution/Installing-the-Unity-Extension>.

W3C. (2018). "World wide web consortium: XML technology." Retrieved on 01/22/2018 from: <https://www.w3.org/standards/xml/>.

Wang, X. and Dunston, P.S. (2011). "Comparative effectiveness of mixed reality-based virtual environments in collaborative design." *IEEE Transactions on Systems, Man and Cybernetics, Part C: Applications and Reviews,* 41(3), pp. 284-296.

Wang, X. Love, P.E. Kim, M.J. and Wang, W. (2014). "Mutual awareness in collaborative design: An Augmented Reality integrated telepresence system." *Computers in Industry,* 65(2), pp. 314-324.

WBDG. (2018). "Whole building design guide" *National Institute of Building Sciences*, Retrieved on 01/05/2018 from: <http://www.wbdg.org>.

Whiskard, H., Jones, D., Voller, S., Snider, C., Gopsill, J. and Hicks, B. (2018). "Mixed reality tools as an enabler for improving operation and maintenance in small and medium enterprises." *Proceedings of International Conference on Product Lifecycle Management, PLM18*, Torino, Italy.

Williams, R. Shayesteh, H. and Marjanovic-Halburd, L. (2014). "Utilising building information modeling for facility management." *International Journal of Facility Management,* 5(1).

Wu, Z. Wang, N. Shao, J. and Deng, G. (2018). "GPU ray casting method for visualizing 3D pipelines in a virtual globe." *International Journal of Digital Earth 2018*, pp. 1-14.

Yabuki, N. Onoue, T. Fukuda, T. and Yoshida, S. (2013). "A heatstroke prediction and prevention system for outdoor construction workers." *Visualization in Engineering,* 1(1), pp. 11.

Yuan, C., (2006). "Markerless pose tracking for augmented reality." *Proceedings of International Symposium on Visual Computing* 2006, Springer, pp. 721-730.

Zhang, C., AlBahnassi, H. and Hammad, A. (2010). "Improving construction safety through real-time motion planning of cranes." *Proceedings of International Conference on Computing in Civil and Building Engineering 2010*, pp. 105-115.

Zhou, F., Duh, H.B. and Billinghurst, M. (2008). "Trends in augmented reality tracking, interaction and display: A review of ten years of ISMAR." *Proceedings of the 7th IEEE/ACM International Symposium on Mixed and Augmented Reality* 2008, IEEE Computer Society, pp. 193-202.

APPENDICES

APPENDIX A: REQUIREMENTS FOR SYSTEM COMPONENTS

Components of MR-based FM applications

It is essential to classify the components for MR-based systems and to define their roles for inspection and maintenance tasks, and also define what technology should be used depending on the task required. For example, inspectors are more interested in "what to inspect?" when they interact visually and physically with the real facility components, whereas maintenance workers are more interested in "how to perform maintenance?". The classification, shown in Table A-1, defines which technology is more suitable for which task. In addition, due to the complexity of the integrated data described in Section 4.3, it is important to classify the visual information so only relevant data will be shown depending on the task required.

Table A-1 MR components and their main roles for inspection and maintenance tasks

Technology		Main roles
Facility Modeling	BIM	The hierarchy structure in BIM allows inspectors to relate the defects to components. It allows maintenance worker to retrieve and visualize building component based on the required task. For example, BIM can be used to show drywalls and inner studs to decide the available spaces to drill a hole for installing a pipe.
	CityGML	An XML-based open data model for representing sets of 3D urban objects. Suitable for large or multi-site facilities (e.g., a campus). The levels of detail provided in CityGML allows users to define the space level (e.g., lobby).
	GIS	Has more use on the urban level and assist FM to locate municipal utilities (e.g., water and sewerage pipes).
Visualization tech.	VR	From the facility management perspective, VR is where all geo-located tasks can be visualized. On-site inspectors have no interest in VR due to the complexity of navigation in the VE to locate themselves and to find the related objects.
	AR	AR-based user interface allows inspector to work freely without the need to visual/search for relevant building elements in a complex building model.
	AV	AV can help the facility manager at the office to compare the video captured by the inspector with the virtual model with matching position.
Tracking tech.	GPS	Suitable for outdoor tracking. Provides georeferenced information about target elements for inspection.
	Gyroscope Inertial tracking	Used to locate and track the field worker.
	CV	CV is used for marker-based and feature-based AR tracking technique.

It is important to define the role of each technology and how it serves the system functionalities. Figure A-1 shows the technology roles in MR-based system including their components. The enhanced MR worlds consider combining several components from several sources. These components are utilized to satisfy three main system requirements: (1) FM requirements, (2) visualization requirements, and (3) collaboration requirements. First, the FM requirements include resources inventory, schedule, and inspection and maintenance records. These components are essential for the MR-based FMS to allow field workers perform their tasks efficiently using location-based data retrieving. Second, the visualization requirements are based on the location-based real world captured data including modeling, images, video, and sensory data. For example, BIM geometric data serve the visualization whereas the non-geometric data serve the collaboration. In addition, real-time tracking is the basic requirement for MR-based visualization, as explained in Section 4.2. Furthermore, Sensors technology (e.g., thermal imaging sensors) can help in the condition assessment and at the same time can support visualization by adding an extra layer of visual information to help the user make the right decision about the defect diagnosis. These components will be reproduced in the VR world to be used as superimposed data in the MR enhanced worlds including IAV and the AR. Third, the collaboration requirements are satisfied by motion tracking technologies and interaction components including gesture-based tracking, audio and messaging communications.

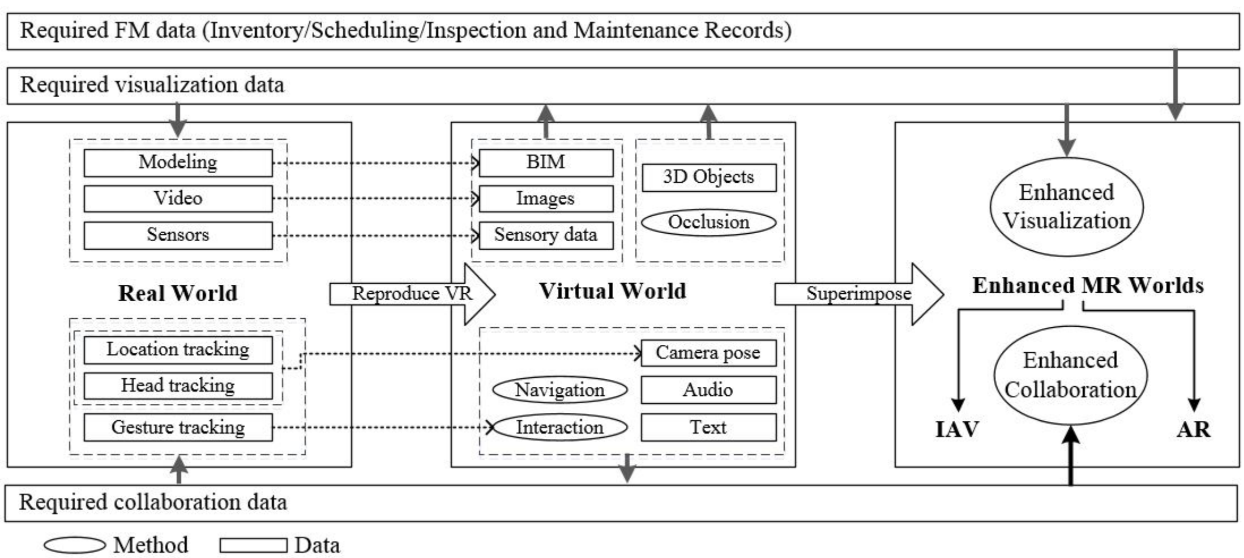


Figure A-1 Technologies roles and the MR-based system components

MR-based communication and collaboration scope

MR applications have the potential to improve FM operations by considering stockholders' visual collaborative approaches. As shown in Figure A-2, the facility manager at the office can utilize MR to communicate with remote suppliers or field workers. Different types of MR can provide specific visual support features. For example, spare parts suppliers can visually collaborate with the facility manager using VR to make decisions about matching or fitting parts. On the other hand, field workers can use AR to benefit from the 3D attributes information, and at the same time keep being aware of their surrounding for their own safety.

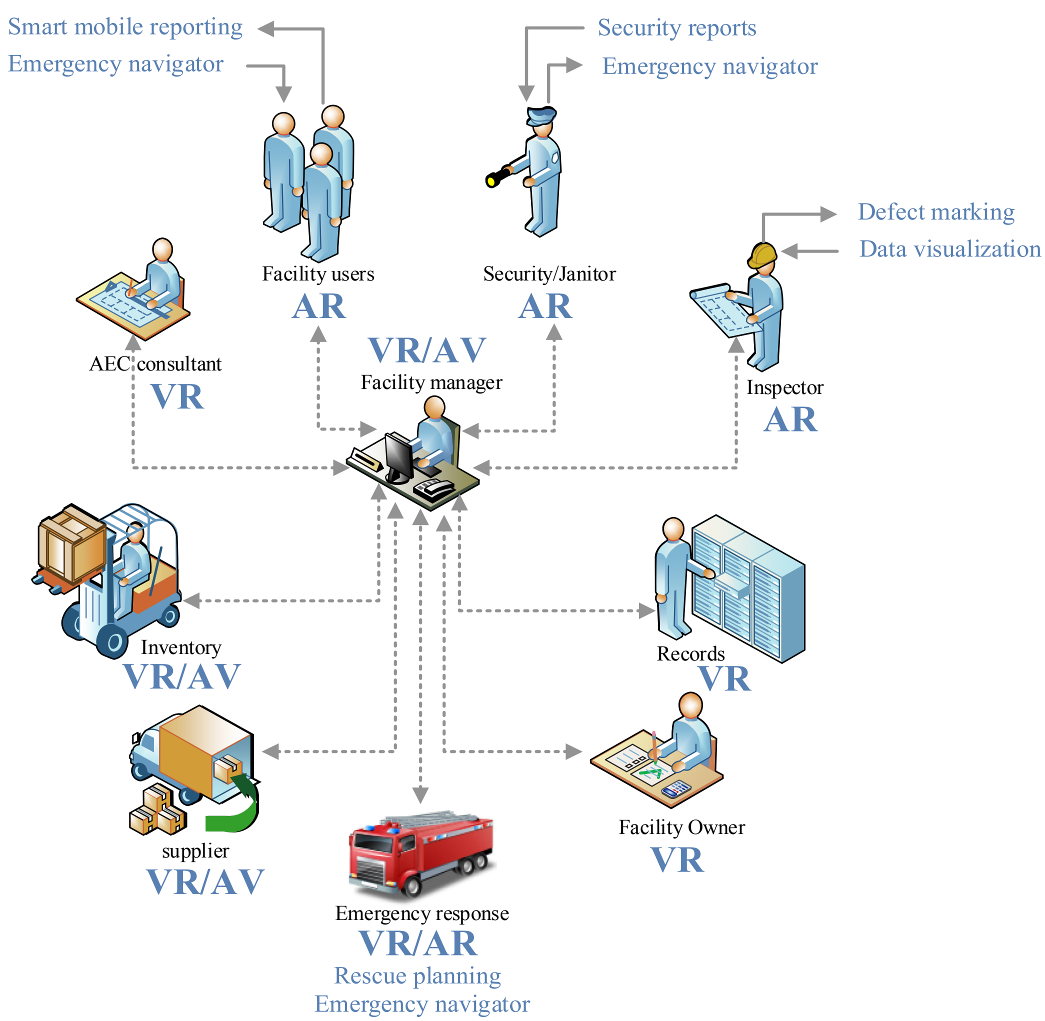


Figure A-2 FM MR communication diagram.

Although there is no single visualization technology that can satisfy the needs of different stakeholders, combining these technologies in cretin settings may provide opportunities to improve Interactive Visual Collaboration (IVC) between them. Furthermore, it is important to understand that these visualization technologies have technical requirements for mobile applications that may mentally or physically interrupt field workers. This kind of interruption may violate the safety code and impact performance.

Modelling components

During maintenance, AR visualization can be based on different points of interest. For instance, the maintenance worker can visualize items with soft materials that can be drilled (e.g., gypsum board). If the maintenance task requires drilling, the worker will be shown only the available places where drilling is allowed. In mobile AR mode, the BIM visual information can be classified to assist the field worker to make the right decision about where to look and perform the required task. For example, the maintenance worker can start the drainage pipe installation task by asking the system to visualize wall geometrical data based on materials (e.g., soft material) so he can easily make a decision about where he can penetrate the wall, which may probably contain hidden studs and structural elements.

Figure A-3 shows an example of visual information. Furthermore, the decision is more supported when the worker is able to visualize the inflammable or electrifying materials so he can perform his task safely. Another example of using this visual classification is to visualize data based on the source of condition where the worker is able to define the humidity source areas (e.g., water pipe), and subsequently he can decide where to install electrical wiring which can be affected by humidity.

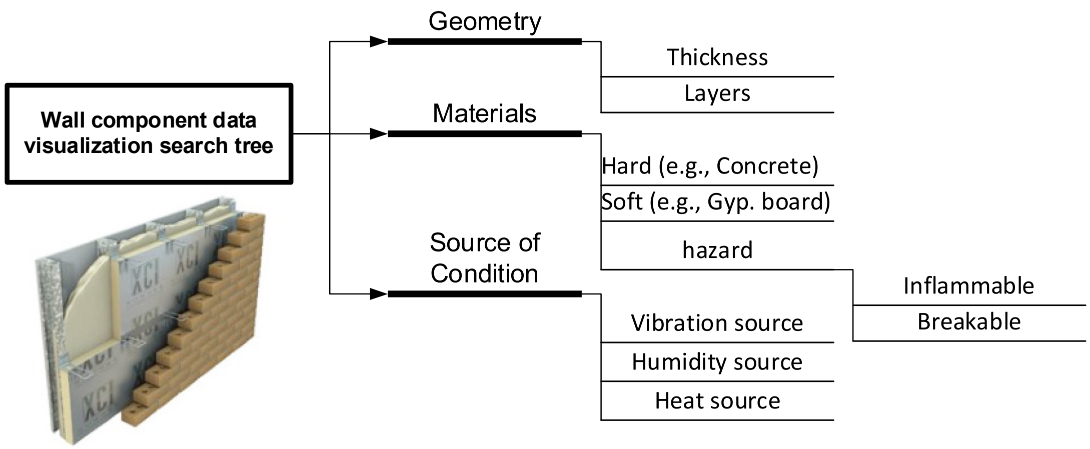


Figure A-3 Classification of visual information.

MR-based visualization components

The role of MR in the research method is essentially to visualize the task-related MR contents from different perspectives to facilitate IVC. For example, installing a pipe inside a wall behind a drywall panel may require a decision from the manager at the office to shift the pipe to a nearby place because of a wire found inside the wall. This decision may delay the process if the traditional method of reporting is followed. This IVC requires sharing, in real time, all necessary facility's geometric and non-geometric data, as well as the pose of the field worker.

In large-scale facilities (e.g., airports), FM is a demanding job with huge workloads, which requires a continuous collaboration between stakeholders. In collaborative MR-based CMMSs, it is important to predefine which visualization technique is suitable to which stakeholder. Therefore, a simple classification has been introduced as shown in Table A-2 to show where each visualization technique (VR, AV, AR) is applicable and to whom (field worker or office facility manager) during inspection and maintenance operations.

FM can interact with both VR and AV during inspection and maintenance tasks. The facility manager can see the marked defects and geotagged photos (F1), generate geo-referenced maintenance and construction tasks or space layout scenarios (F2), and review maintenance and construction tasks or space layout results, support workers and make decision (F3). On the other hand, the field worker (W) can interact with the real world using AR during inspection and maintenance operations. The field worker can visualize inspection and maintenance tasks or space layout scenarios generated by the facility manager and share the result (W4).

Table A-2 The use of visualization techniques for inspection and maintenance tasks.

FM scope	Virtual Reality	Augmented Virtuality	Augmented Reality	Reality
- Inspection	F1	F1	W	W
- Maintenance	F2	F3	W4	W
- Renovation				
- Replacement				
- Reconstruction				

W = Field Worker F= Facility manager

Based on Milgram's virtuality continuum discussed in Chapter 2, this research investigates the levels of augmenting objects rendering for FM. Figure A-4 illustrates the level of rendering depends of the required task. For example, augmenting by a textual annotation on a real view can be enough for adding informative data for guiding purposes. In addition, augmenting by adding detailed highlighted 3D contents can be useful for inspection or maintenance tasks.

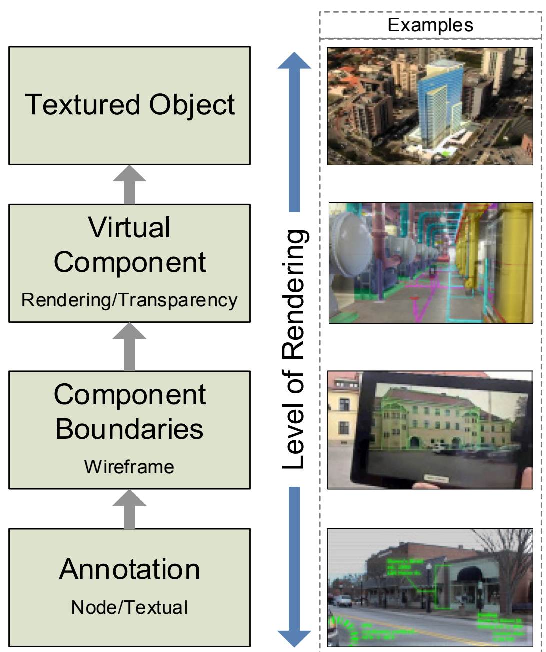


Figure A-4 Levels of rendering for MR FMSs.

Levels of tracking for MR-based FMSs

In indoor MR applications, accurate alignment of the augmented graphical or textual information related to the assigned task cannot always be achieved using only RTLS tracking devices. Therefore, CV technology can be used and combined with RTLSs (e.g., Wi-Fi, UWB) to improve tracking. This tracking method can provide acceptable accuracy to locate building elements in AR and VR environments. However, CV feature-based tracking accuracy depends on many factors such as good trackable features, light conditions, and other image processing issues including illumination levels, camera resolution and FOV.

Figure A-5 illustrates the tracking accuracy levels to fit with the required FM task needs. For example, locating a defected element requires less accuracy and locating a defect on an element requires more accuracy. The levels of accuracy range from building component level to an urban level. Each level requires specific tracking technologies which can be combined in some cases to improve tracking accuracy.

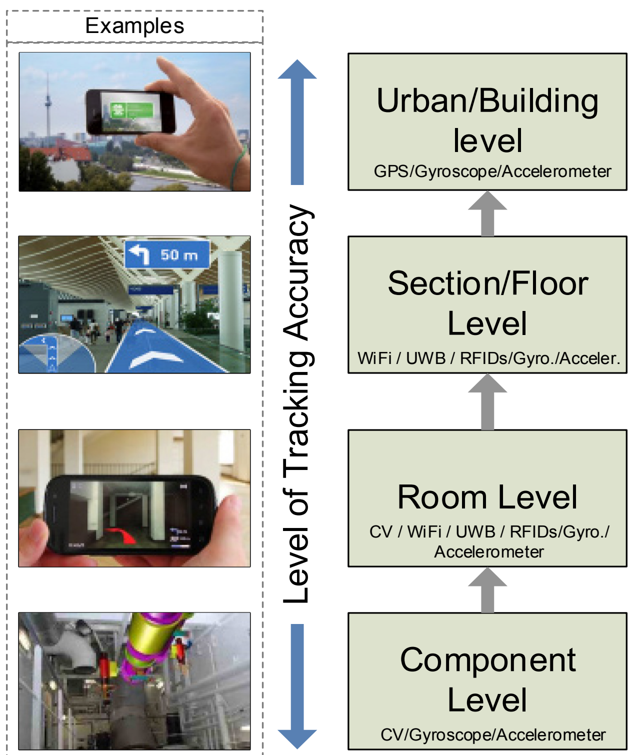


Figure A-5 Tracking accuracy levels for MR FMSs.

APPENDIX B: ADDITIONAL MATERIALS RELATED TO IMPLEMENTATION

Figure B-1 illustrates the processes of producing the *Virtual Hatch*. The processes include: (1) Data preprocessing, (2) Real-time on-site processes. The, the rendering requirements with the modeled data are reproduced for real-time rendering. The real-time onsite processes involve rendering of video and 3D contents and AR-based visualization. The AR module are supported with interaction methods including: (a) object picking for assigning defects markers or selecting a facility component; (b) object dragging for controlling the virtual hatch size and position. This interaction requires accurate pose information, which will be provided by CV feature-based tracking and tablet sensors (i.e., gyroscope and accelerometer).

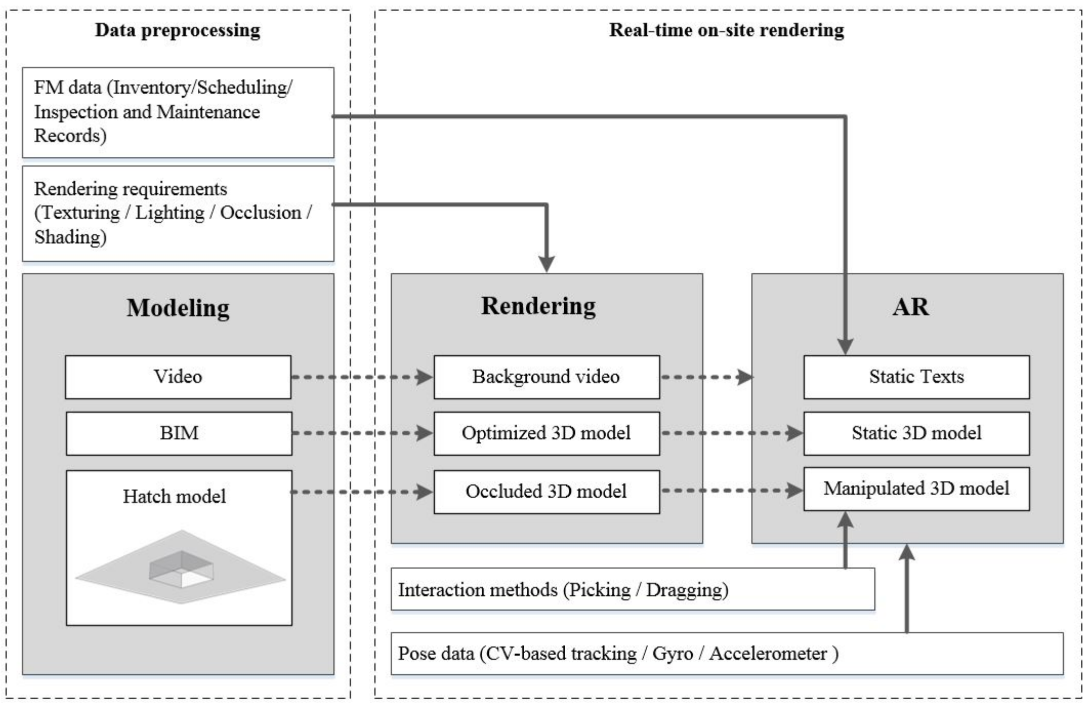


Figure B-1 Producing virtual hatch process.

When the field worker navigates using the tablet-based AR module, the virtual hatch is positioned using the intersecting hit point (P_2) between the virtual ray and the element collider (e.g., a wall). The virtual ray is generated using the Raycast technique used for element marking. The virtual hatch position is updated each time the field worker changes the tablet orientation. Despite the location of the field worker, the orientation of the virtual hatch is restricted to only six perpendicular orientations, as shown in Figure B-2. Once the virtual hatch positioned on the right place, its movement will be restricted to two directions on the detected surface until a new surface is detected. The VH direction updates automatically and its new orientation is calculated automatically based on the user position and the facing surface. For example, if the user directs the tablet towards the false ceiling, the VH will rotate in its Y-direction -180º and if he/she decided to rotate towards the floor, the Y rotation value will be the default value which is 0º.

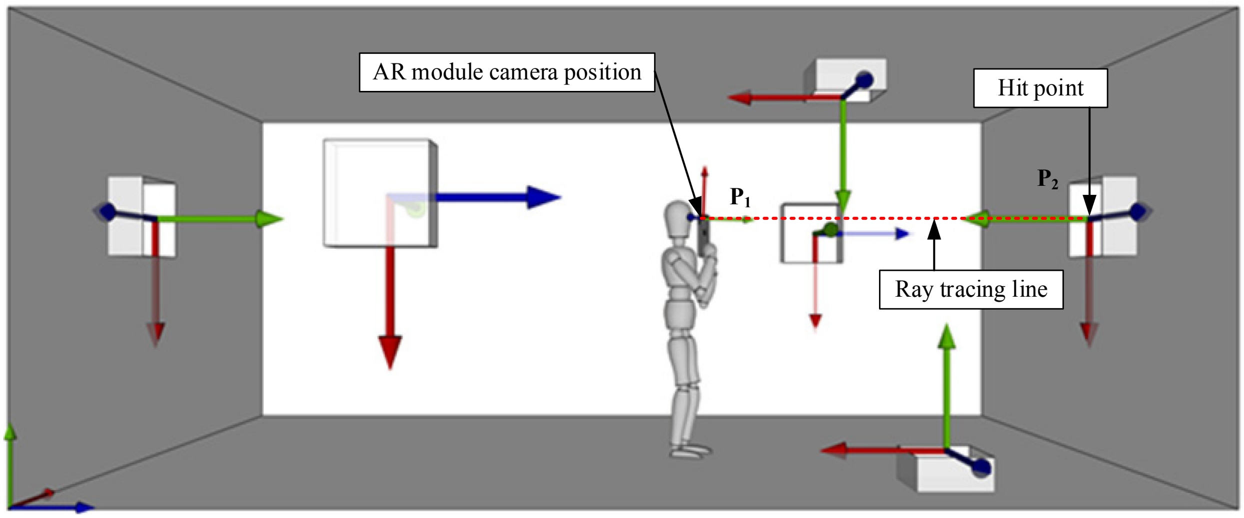


Figure B-2 Virtual Hatch automatic alignment with surfaces.

Feature-based tracking database

The tracking data can be processed to improve feature detection. Figure B-3 illustrates the process of generating feature-based tracking. After collecting space photos, as discussed in Section 3.5, feature-based tracking engine (e.g., Vuforia) is used to generate tracking data based on the collected images and save it in the *Tracking Database.* After camera photo frame is pixelated and features are detected using Tracker, the state object is updated and pushed to update the new augmenting object new position and rendering the resulting scene. Since the tracker is reading binary pictures, the raw images can be processed before generating the feature-based tracking data to improve their quality. This can be done by enhancing their brightness and contrast as shown in Section 6.3.4.

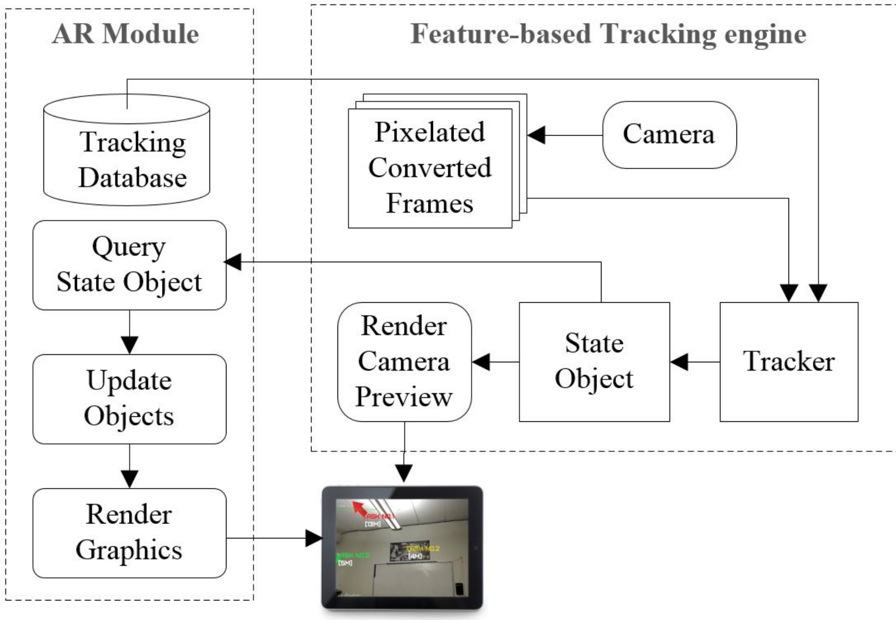


Figure B-3 Feature-based tracking process in CBIM3R-FMS.

Gesture-based MR interaction for IAV module

Since the facility manager is totally immersed in the VE and he has no visual connection with his surrounding, it will be difficult for him to utilize any physical input devices such as joysticks. Therefore, it is important to allow him to see his hands and fingers movements in the VE. Furthermore, the user gesture can be tracked and used to update the virtual hands. Figure B-4 illustrates the setting for combining gesture-based tracking technology with the head tracking camera. This allows the simultaneous tracking of both the head and hands movements. These tracking data are used to interact with the IAV environment and to move the virtual hands. Tracking the IAV user's hands is important to allow him interacting with the VE.

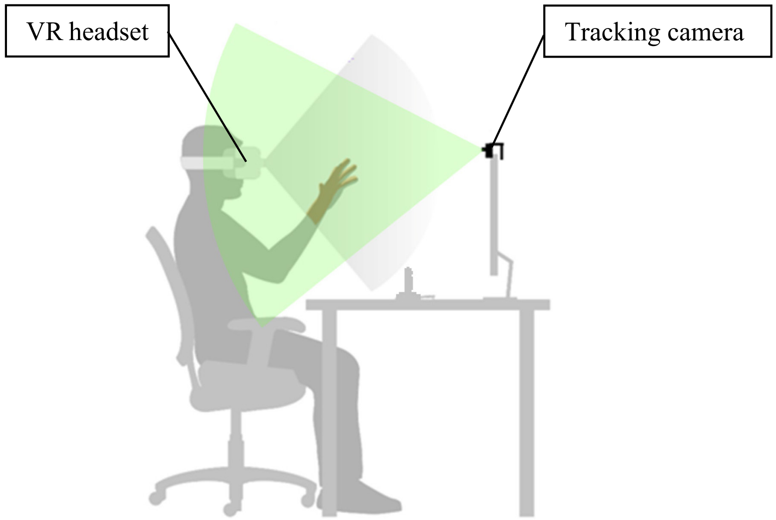


Figure B-4 Combining gesture-based tracking with head tracking.

Figure B-5 illustrates the suitable tracking ranges for CBIM3R-FMS for both the head and gesture tracking devices. The tracking range of the HMD's 6-DOF movements (i.e., 3-axis rotational tracking and 3-axis positional tracking) forms a pyramid-shaped FOV, which defines the camera range of tracking.

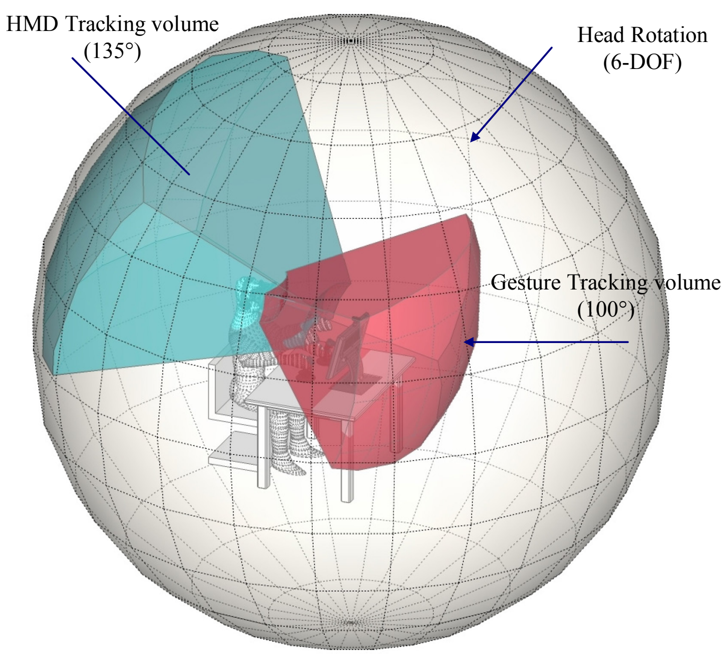


Figure B-5 CBIM3R-FMS head and gesture tracking volumes.

Figure B-6 shows the different coordinate systems using the gesture-based interaction with the VE in IAV module.

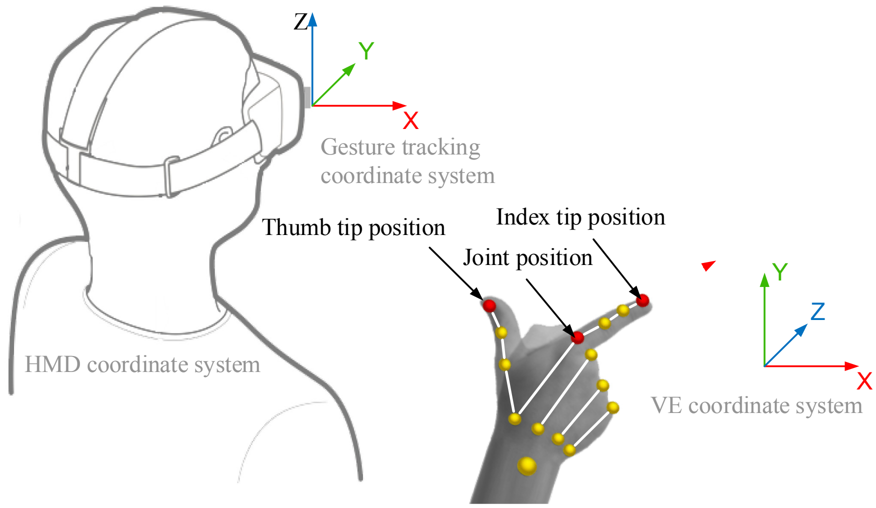


Figure B-6 Different coordinate systems using the gesture-based interaction in IAV module.

Defect marking in AR module

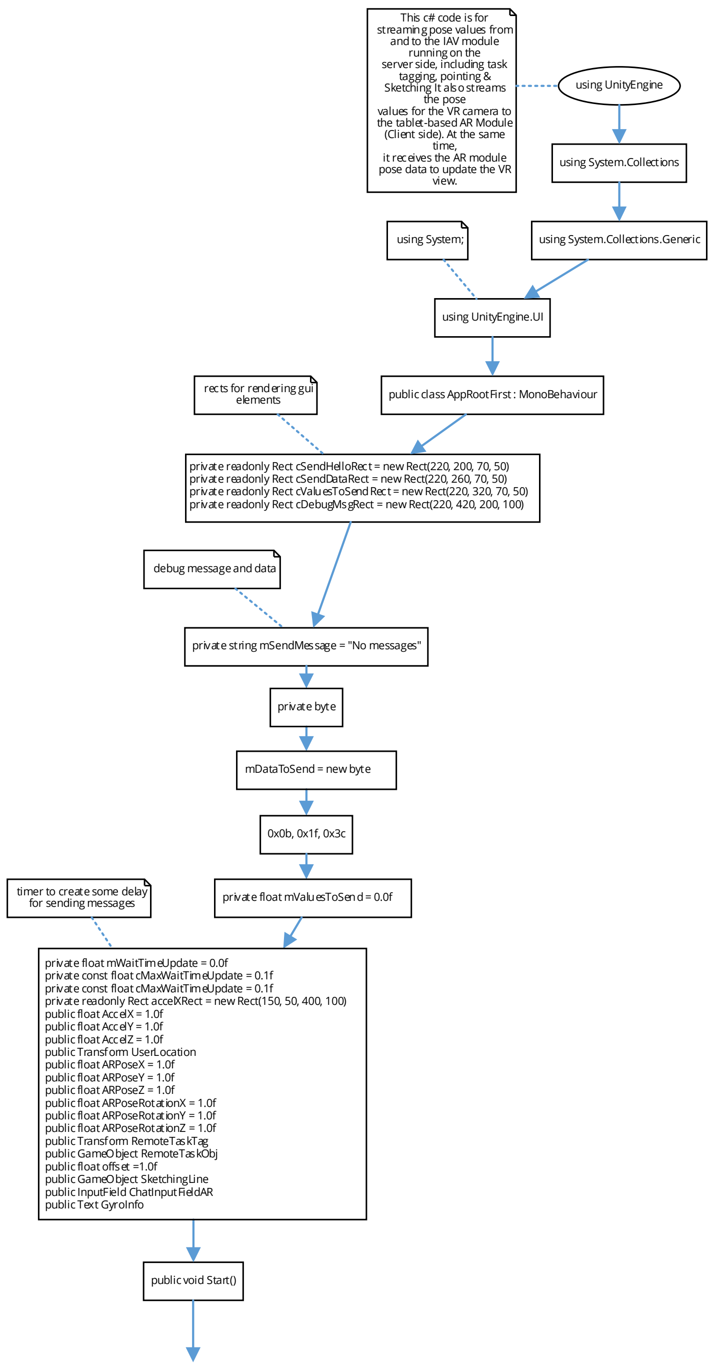
There are two types of picking in this research. First, the picking done by the facility manager to assign tasks in IAV module. Second, the picking done by the field worker to mark defects in the AR module. Picking is the process of selecting shapes in the 3D objects using the 2D coordinates of the picking point. The pick object can be a ray, which is extended from the finger picking position through the VE. When a pick is requested, pickable objects that intersect with the pick object are computed. The pick returns a list of objects, from which the nearest object can be computed (e.g. a wall). The intersection between the ray and the 3D object is used as a center point of the defect mark (e.g., sphere).

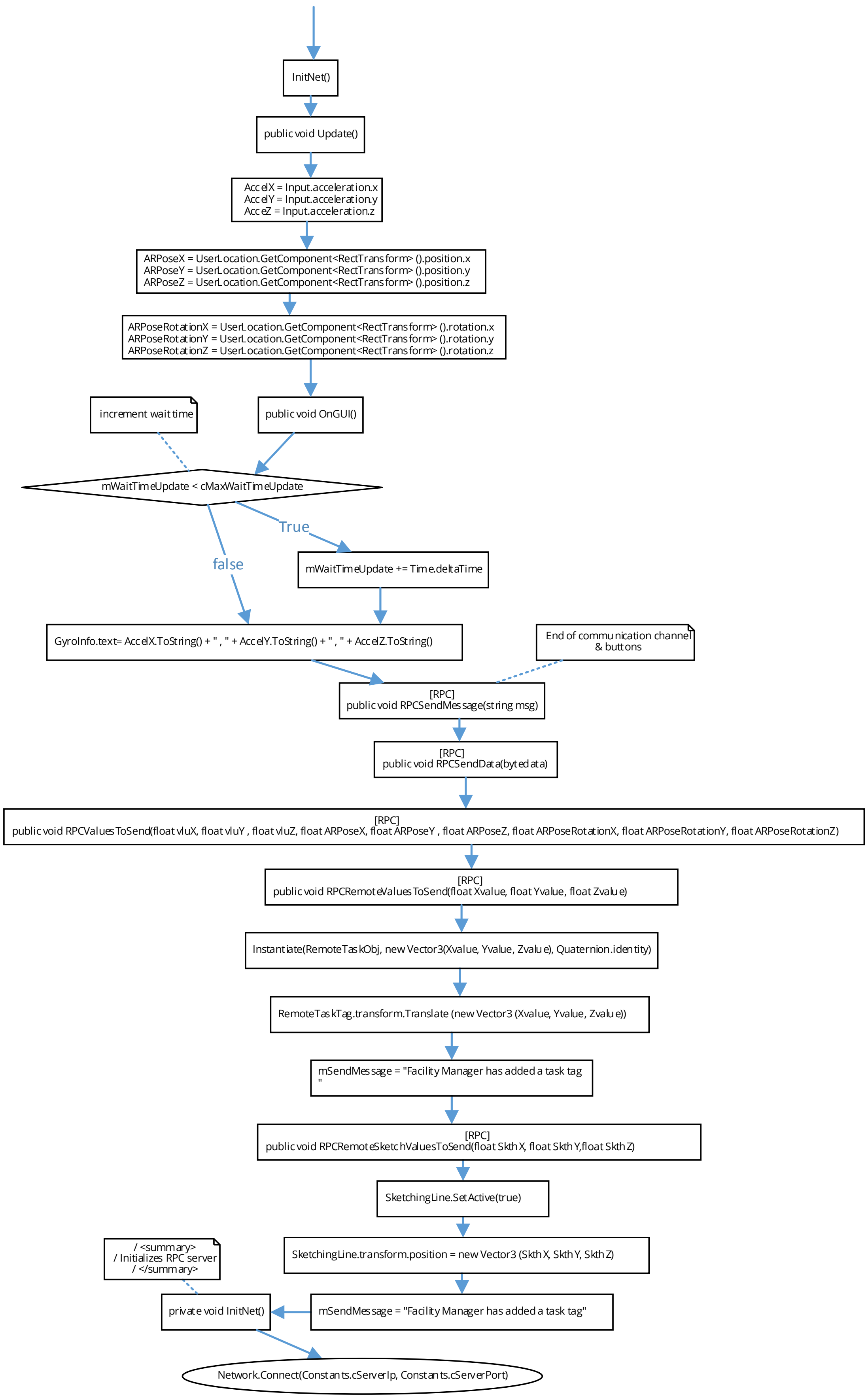
An application that is facilitated by picking in the proposed framework is adding an object to the VE, such as adding a defect to a building element (e.g., a column). In the case of structural element inspection, inspector can mark defects by picking a virtual element in the EV. These defects are represented by 3D objects (e.g., a sphere), on the surface of the inspected element.

APPENDIX C: INTERACTIVE VISUAL COLLABORATION (IVC) CODE

The following codes are chosen based on their importance and contribution to develop the interactive visual collaboration mode.

Server Side (IAV module):

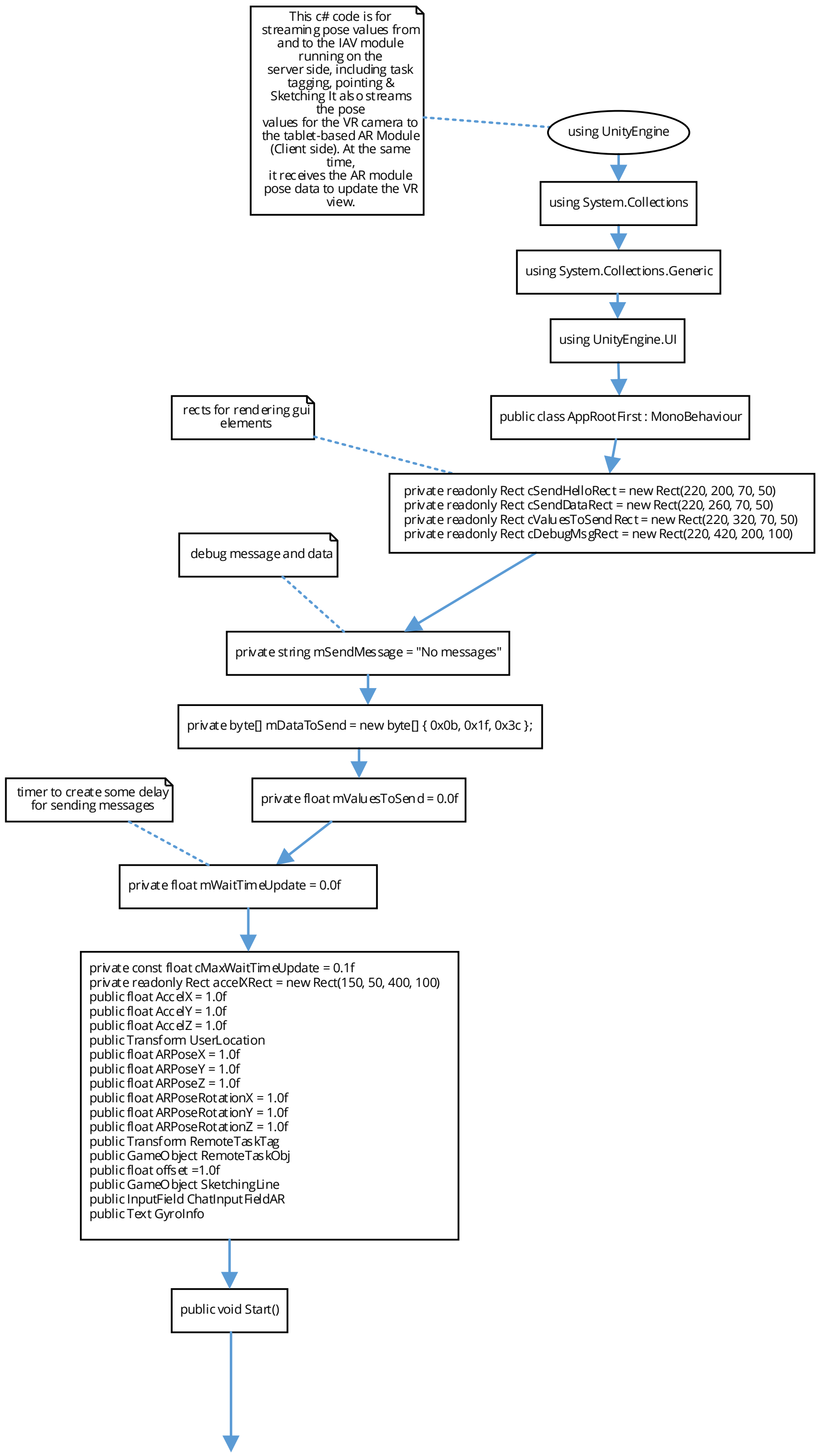


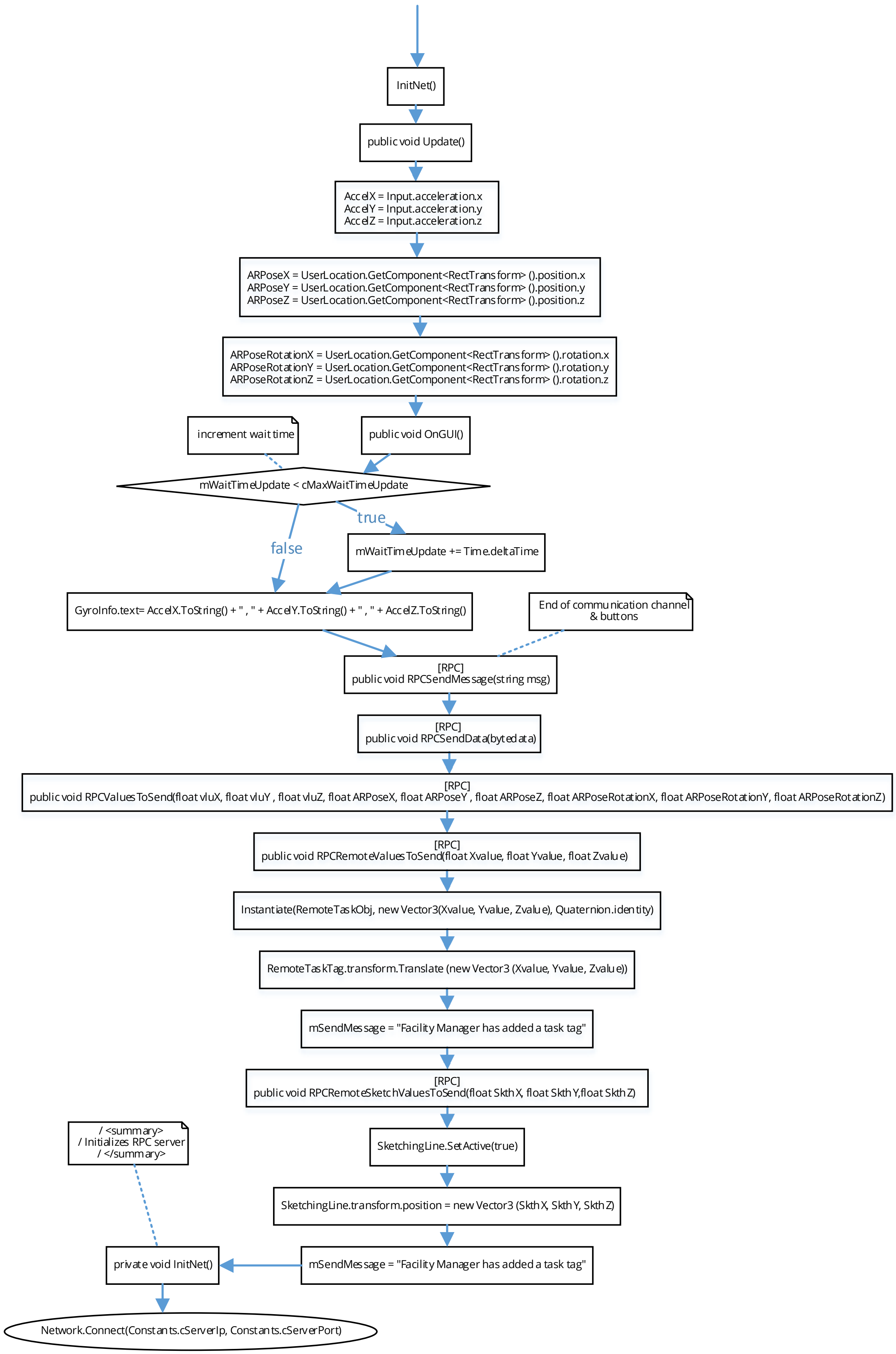

InitNet()
public void Update()
AccelX = Input.acceleration.x
AccelY = Input.acceleration.y
AcceZ = Input.acceleration.z
ARPoseX = UserLocation.GetComponent<RectTransform> ().position.x
ARPoseY = UserLocation.GetComponent<RectTransform> ().position.y
ARPoseZ = UserLocation.GetComponent<RectTransform> ().position.z
ARPoseRotationX = UserLocation.GetComponent<RectTransform> ().rotation.x
ARPoseRotationY = UserLocation.GetComponent<RectTransform> ().rotation.y
ARPoseRotationZ = UserLocation.GetComponent<RectTransform> ().rotation.z
increment wait time
public void OnGUI()
mWaitTimeUpdate < cMaxWaitTimeUpdate
True
false
mWaitTimeUpdate += Time.deltaTime
GyroInfo.text= AccelX.ToString() + " , " + AccelY.ToString() + " , " + AccelZ.ToString()
End of communication channel & buttons
[RPC] public void RPCSendMessage(string msg)
[RPC] public void RPCSendData(byte data)
[RPC] public void RPCValuesToSend(float vluX, float vluY , float vluZ, float ARPoseX, float ARPoseY , float ARPoseZ, float ARPoseRotationX, float ARPoseRotationY, float ARPoseRotationZ)
[RPC] public void RPCRemoteValuesToSend(float Xvalue, float Yvalue, float Zvalue)
Instantiate(RemoteTaskObj, new Vector3(Xvalue, Yvalue, Zvalue), Quaternion.identity)
RemoteTaskTag.transform.Translate (new Vector3 (Xvalue, Yvalue, Zvalue))
mSendMessage = "Facility Manager has added a task tag "
[RPC] public void RPCRemoteSketchValuesToSend(float SkthX, float SkthY,float SkthZ)
SketchingLine.SetActive(true)
SketchingLine.transform.position = new Vector3 (SkthX, SkthY, SkthZ)
/ <summary>
/ Initializes RPC server
/ </summary>
private void InitNet()
mSendMessage = "Facility Manager has added a task tag"
Network.Connect(Constants.cServerIp, Constants.cServerPort)

```
/*
 This c# code is for streaming pose values from and to the IAV module running on the
 server side, including task tagging, pointing & Sketching It also streams the pose
 values for the VR camera to the tabletbased AR Module (Client side). At the same time,
 it receives the AR module pose data to update the VR view.
*/

using UnityEngine;
using System.Collections;
using System.Collections.Generic;
using UnityEngine.UI;

public class AppRootFirst : MonoBehaviour
{
    ///////////////////////////////////////////////////////////////////////////
    // rects for rendering gui elements
    private readonly Rect cSendHelloRect = new Rect(220, 200, 70, 50);
    private readonly Rect cSendDataRect = new Rect(220, 260, 70, 50);
    private readonly Rect cValuesToSendRect = new Rect(220, 320, 70, 50);
    private readonly Rect cDebugMsgRect = new Rect(220, 420, 200, 100);
    // debug message and data
    private string mSendMessage = "No messages";
    private byte[] mDataToSend = new byte[] { 0x0b, 0x1f, 0x3c };
    private float mValuesToSend = 0.0f;
    // timer to create some delay for sending messages
    private float mWaitTimeUpdate = 0.0f;
    private const float cMaxWaitTimeUpdate = 0.1f;
    private readonly Rect accelXRect = new Rect(150, 50, 400, 100);
    public float AccelX = 1.0f;
    public float AccelY = 1.0f;
    public float AccelZ = 1.0f;
    public Transform UserLocation;
    public float ARPoseX = 1.0f;
    public float ARPoseY = 1.0f;
    public float ARPoseZ = 1.0f;
    public float ARPoseRotationX = 1.0f;
    public float ARPoseRotationY = 1.0f;
    public float ARPoseRotationZ = 1.0f;
    public Transform RemoteTaskTag;
    public GameObject RemoteTaskObj;
    public float offset =1.0f;
    public GameObject SketchingLine;
    public InputField ChatInputFieldAR;
    public Text GyroInfo;

    public void Start()
    {
        InitNet();
    }
    public void Update()
    {
        AccelX = Input.acceleration.x;
        AccelY = Input.acceleration.y;
        AccelZ = Input.acceleration.z;
        ARPoseX = UserLocation.GetComponent<RectTransform> ().position.x;
        ARPoseY = UserLocation.GetComponent<RectTransform> ().position.y;
        ARPoseZ = UserLocation.GetComponent<RectTransform> ().position.z;
```

```
        ARPoseRotationX = UserLocation.GetComponent<RectTransform> ().rotation.x;
        ARPoseRotationY = UserLocation.GetComponent<RectTransform> ().rotation.y;
        ARPoseRotationZ = UserLocation.GetComponent<RectTransform> ().rotation.z;
    }
    public void OnGUI()
    {
        // increment wait time
        if (mWaitTimeUpdate < cMaxWaitTimeUpdate)
        {
            mWaitTimeUpdate += Time.deltaTime;
        }
        GyroInfo.text= AccelX.ToString() + " , " + AccelY.ToString() + " , " + AccelZ.ToString();
    }
//    End of communication channel & buttons

    public void SendMessage(string msg)
    {

    }

    public void SendData(byte[] data)
    {

    }

    public void ValuesToSend(float vluX, float vluY , float vluZ, float ARPoseX, float ARPoseY , float ARPoseZ, float ARPoseRotationX, float ARPoseRotationY, float ARPoseRotationZ)
    {

    }

    public void emoteValuesToSend(float Xvalue, float Yvalue, float Zvalue)
    {
        Instantiate(RemoteTaskObj);
        RemoteTaskTag.transform.Translate (new Vector3 (Xvalue, Yvalue, Zvalue));
        mSendMessage = "Facility Manager has added a task tag";
    }

    public void RemoteSketchValuesToSend(float SkthX, float SkthY,float SkthZ)
    {

        SketchingLine.SetActive(true);
        SketchingLine.transform.position = new Vector3 (SkthX, SkthY, SkthZ);
                mSendMessage = "Facility Manager has added a task tag";
            }


            private void InitNet()
            {
                Network();

            }

        }
```

Client Side (AR module):



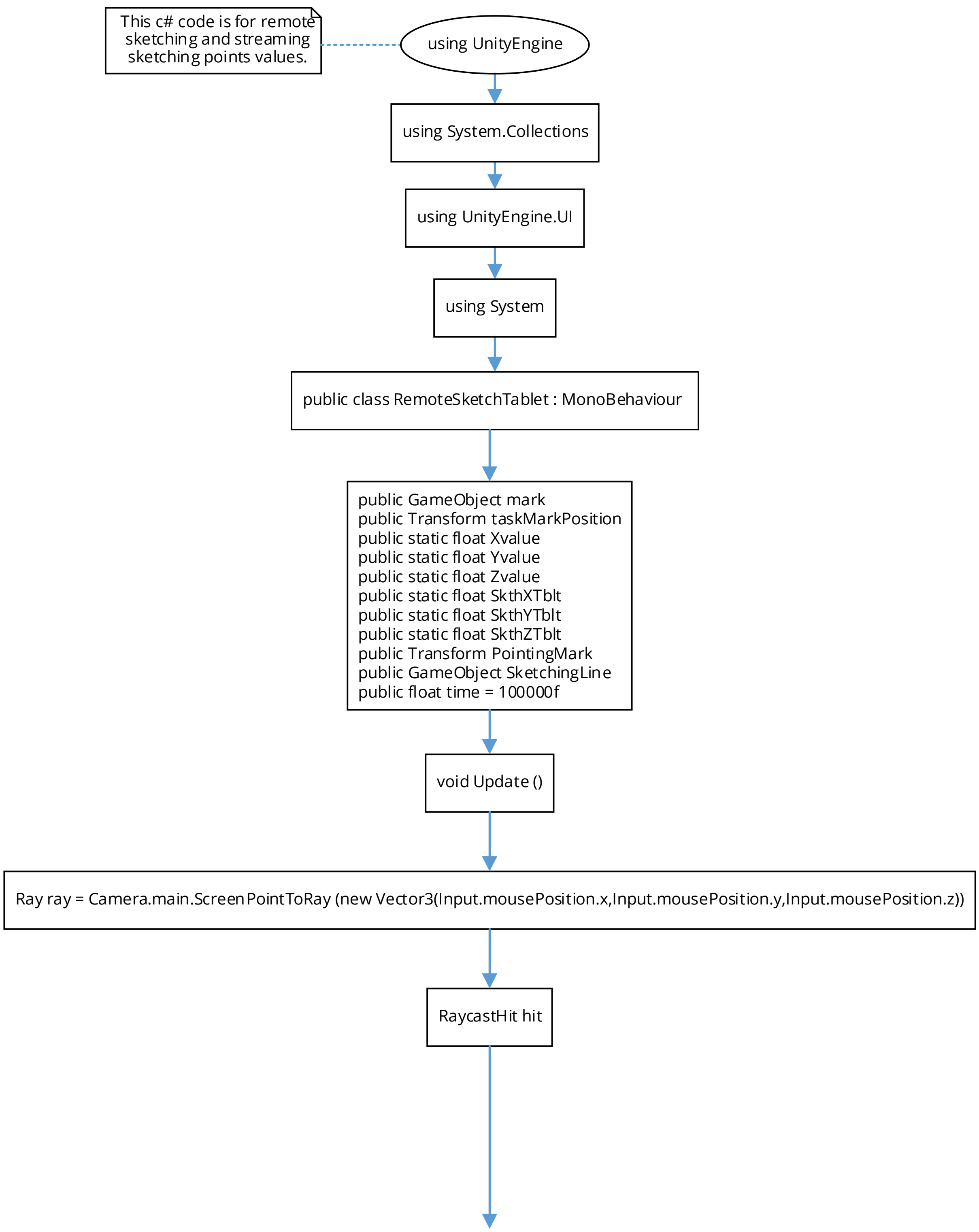

InitNet()
public void Update()
AccelX = Input.acceleration.x
AccelY = Input.acceleration.y
AccelZ = Input.acceleration.z
ARPoseX = UserLocation.GetComponent<RectTransform> ().position.x
ARPoseY = UserLocation.GetComponent<RectTransform> ().position.y
ARPoseZ = UserLocation.GetComponent<RectTransform> ().position.z
ARPoseRotationX = UserLocation.GetComponent<RectTransform> ().rotation.x
ARPoseRotationY = UserLocation.GetComponent<RectTransform> ().rotation.y
ARPoseRotationZ = UserLocation.GetComponent<RectTransform> ().rotation.z
increment wait time
public void OnGUI()
mWaitTimeUpdate < cMaxWaitTimeUpdate
true
false
mWaitTimeUpdate += Time.deltaTime
GyroInfo.text= AccelX.ToString() + " , " + AccelY.ToString() + " , " + AccelZ.ToString()
End of communication channel & buttons
[RPC] public void RPCSendMessage(string msg)
[RPC] public void RPCSendData(bytedata)
[RPC] public void RPCValuesToSend(float vluX, float vluY , float vluZ, float ARPoseX, float ARPoseY , float ARPoseZ, float ARPoseRotationX, float ARPoseRotationY, float ARPoseRotationZ)
[RPC] public void RPCRemoteValuesToSend(float Xvalue, float Yvalue, float Zvalue)
Instantiate(RemoteTaskObj, new Vector3(Xvalue, Yvalue, Zvalue), Quaternion.identity)
RemoteTaskTag.transform.Translate (new Vector3 (Xvalue, Yvalue, Zvalue))
mSendMessage = "Facility Manager has added a task tag"
[RPC] public void RPCRemoteSketchValuesToSend(float SkthX, float SkthY,float SkthZ)
/ <summary> / Initializes RPC server / </summary>
SketchingLine.SetActive(true)
SketchingLine.transform.position = new Vector3 (SkthX, SkthY, SkthZ)
private void InitNet()
mSendMessage = "Facility Manager has added a task tag"
Network.Connect(Constants.cServerIp, Constants.cServerPort)

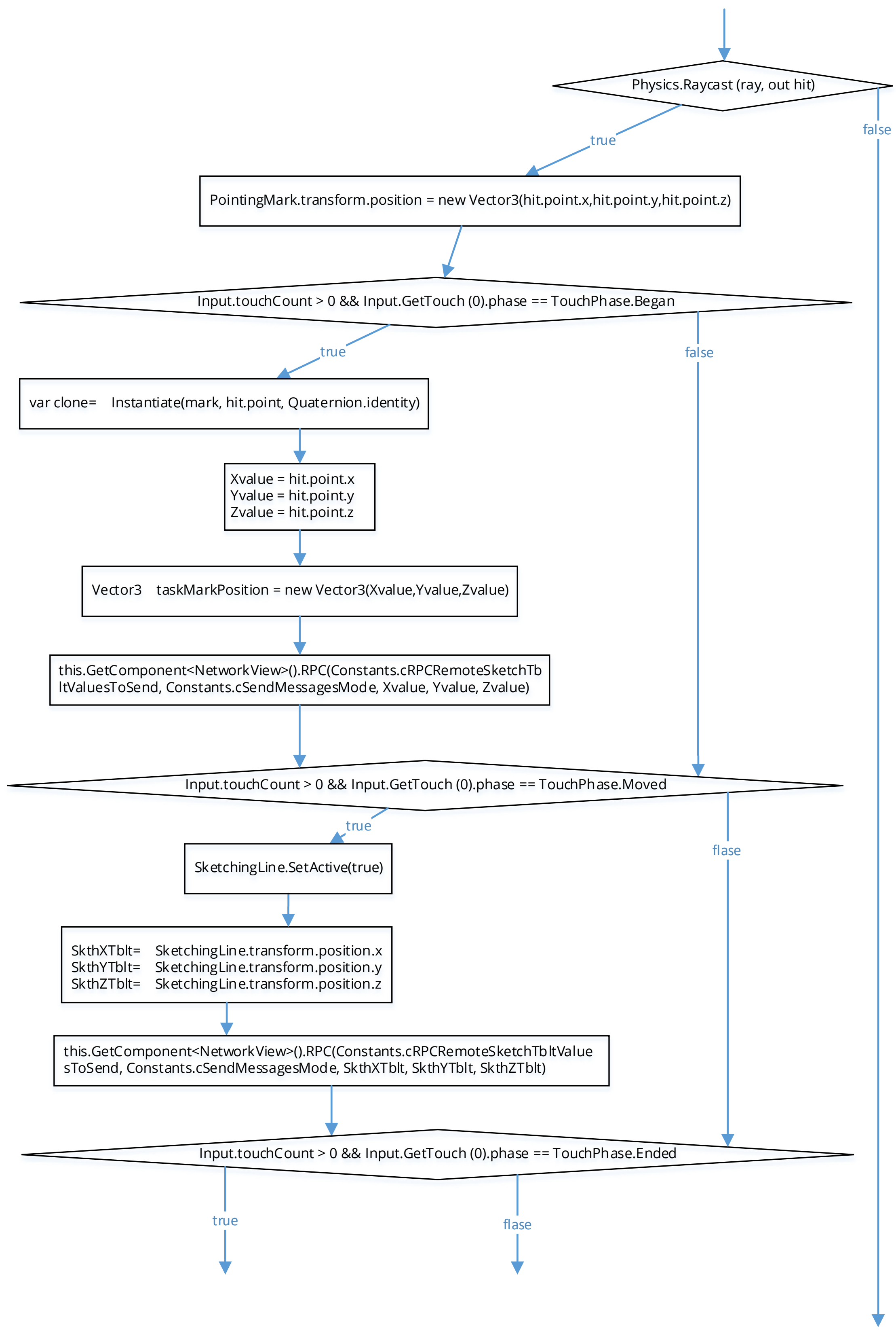
```
/*
 This c# code is for streaming pose values from and to the AR module running on the
 Client side, including task tagging, pointing & Sketching It also streams the pose
 values for the tablet camera to the IAV Module (Server side).
*/

using UnityEngine;
using System.Collections;
using System.Collections.Generic;
using UnityEngine.UI;

public class AppRootSecond : MonoBehaviour
{
    ///////////////////////////////////////////////////////////////////////////

    // rect for displaying of received message
    private readonly Rect cMsgRect = new Rect(20, 420, 200, 100);
    // received message
    private string mReceiveMessage = "";
    public string msg;
    public double numberx;
    public Transform Cam;
    public InputField ChatInputField;
    public GameObject RemoteTaskObj;
    public GameObject SketchingLine;
    public InputField NoteInputField;
    public Transform TabletAvatar;
    public GameObject logger;

    ///////////////////////////////////////////////////////////////////////////
    public void Start()
    {
        InitNet();
    }

    public void Update()
    {
        if (Input.anyKey)
        foreach (char c in Input.inputString)
        {
            if (c == '\b') // has backspace/delete been pressed?
            {

                    logger.SetActive (true);

            }
                 if  (c == '\\') // enter/return
            {
                    logger.SetActive (false);
            }
        }
    }

    public void OnGUI()
    {
        // just show received message
        GUI.Label(cMsgRect, mReceiveMessage);
    }
```

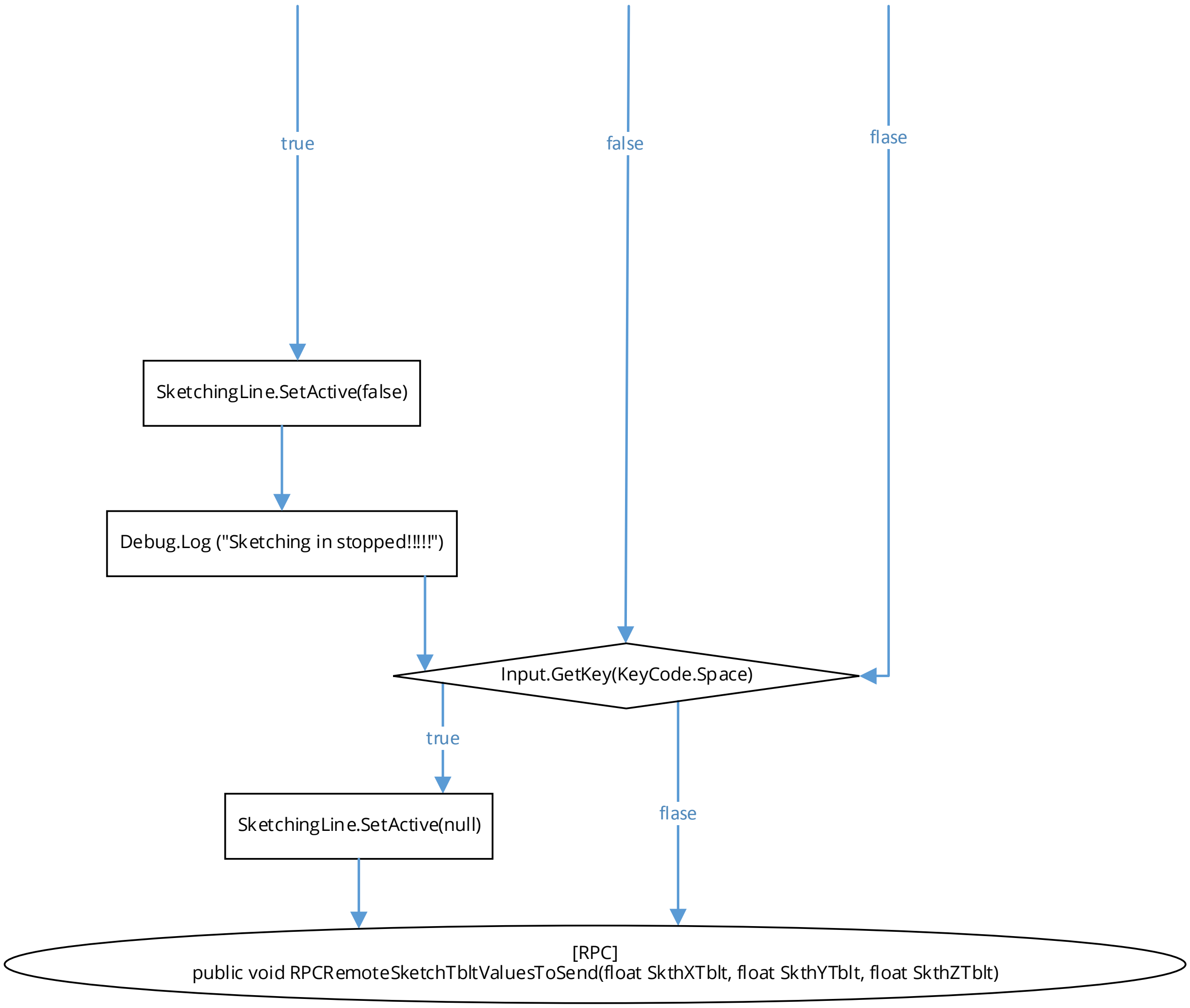
```
    public void SendMessage(string msg)
    {
        mReceiveMessage = "Message received = " + msg;
        Debug.Log("The passed Gyro values are:" + msg);

    }


    public void SendData(byte[] data)
    {
        mReceiveMessage = "Data received. Data length = " + data.Length;
    }


    public void ValuesToSend(float vluX, float vluY , float vluZ, float ARPoseX, float ARPoseY , float ARPoseZ, float ARPoseRotationX, float ARPoseRotationY, float ARPoseRotationZ)
    {
        mReceiveMessage = "Message received = " + vluX;
        Debug.Log("The passed Gyro values are:" + vluX +" , "+ vluY +" , "+ vluZ +" , "+ ARPoseX +" , "+ ARPoseY +" , "+ ARPoseZ+" , "+ ARPoseRotationX +" , "+ ARPoseRotationY +" , "+ ARPoseRotationZ);
        Cam.transform.position= new Vector3(ARPoseX,ARPoseY,ARPoseZ);
    }

    public void RemoteValuesToSend(float fXvalue, float fYvalue, float fZvalue)
    {

    }

    public void RemoteFeildValuesToSend(float fXvalue, float fYvalue, float fZvalue)

    {
        Instantiate(RemoteTaskObj);

    }


    public void RPCRemoteSketchTbltValuesToSend(float SkthXTblt, float SkthYTblt, float SkthZTblt)
    {
        SketchingLine.SetActive(true);
        SketchingLine.transform.position = new Vector3 (SkthXTblt, SkthYTblt, SkthZTblt);

            }


            public void RemoteNote(string usernoteTxt)
            {
                NoteInputField.text = usernoteTxt;
            }


            public void RemoteTabletPose(float ARPoseX, float ARPoseY , float ARPoseZ , float ARPoseRotationX, float ARPoseRotationY, float ARPoseRotationZ )
            {
```

```
                TabletAvatar.transform.position = new Vector3 (ARPoseX, ARPoseY, ARPoseZ);
            }


            private void InitNet()
            {
                    Network.InitializeServer();

            }

            #endregion
            #region Properties

            #endregion
        }
```

Local and Remote Sketching for AR module:



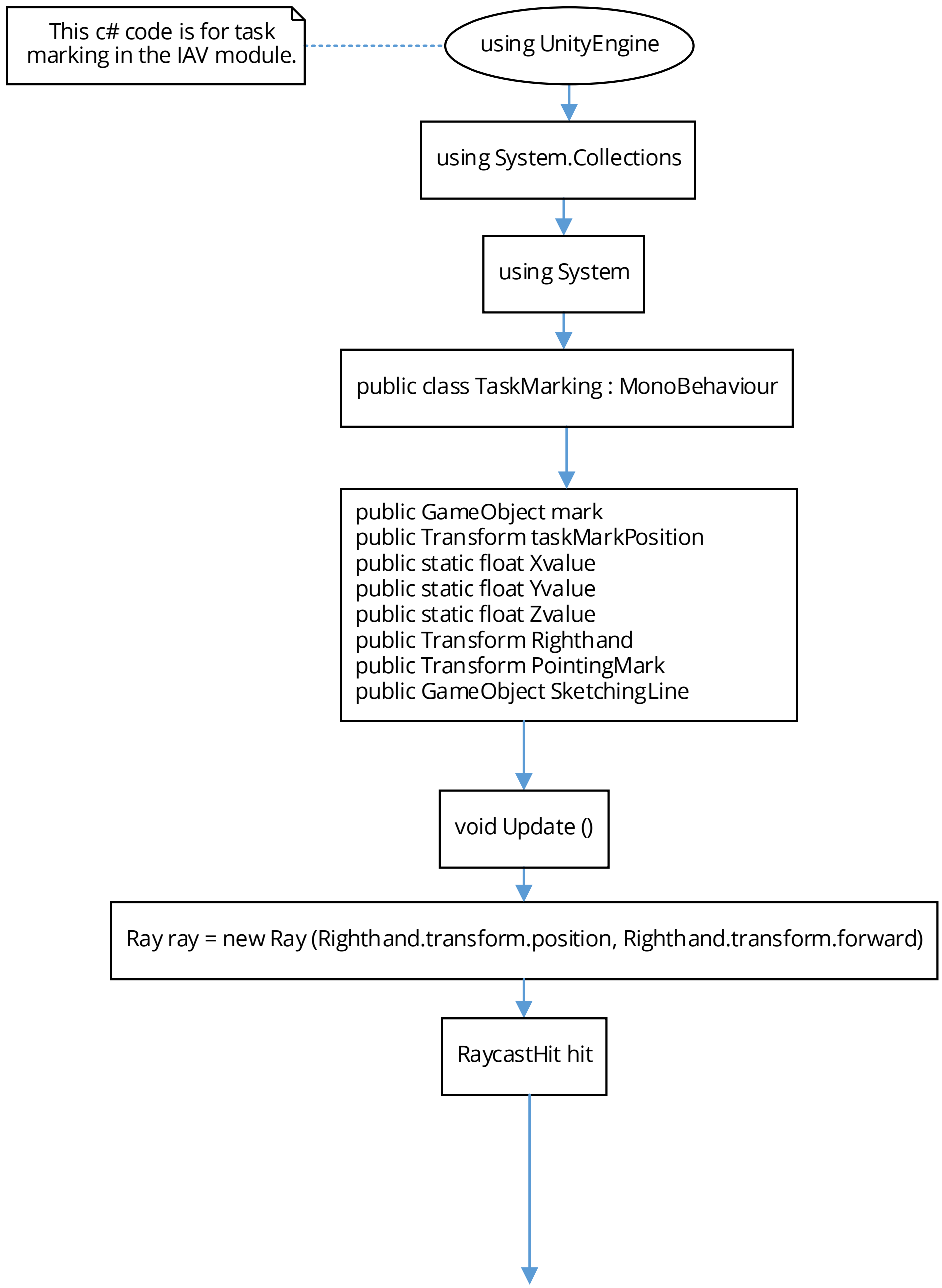

Physics.Raycast (ray, out hit)
true
false
PointingMark.transform.position = new Vector3(hit.point.x,hit.point.y,hit.point.z)
Input.touchCount > 0 && Input.GetTouch (0).phase == TouchPhase.Began
true
false
var clone= Instantiate(mark, hit.point, Quaternion.identity)
Xvalue = hit.point.x
Yvalue = hit.point.y
Zvalue = hit.point.z
Vector3 taskMarkPosition = new Vector3(Xvalue,Yvalue,Zvalue)
this.GetComponent<NetworkView>().RPC(Constants.cRPCRemoteSketchTbltValuesToSend, Constants.cSendMessagesMode, Xvalue, Yvalue, Zvalue)
Input.touchCount > 0 && Input.GetTouch (0).phase == TouchPhase.Moved
true
flase
SketchingLine.SetActive(true)
SkthXTblt= SketchingLine.transform.position.x
SkthYTblt= SketchingLine.transform.position.y
SkthZTblt= SketchingLine.transform.position.z
this.GetComponent<NetworkView>().RPC(Constants.cRPCRemoteSketchTbltValuesToSend, Constants.cSendMessagesMode, SkthXTblt, SkthYTblt, SkthZTblt)
Input.touchCount > 0 && Input.GetTouch (0).phase == TouchPhase.Ended
true
flase

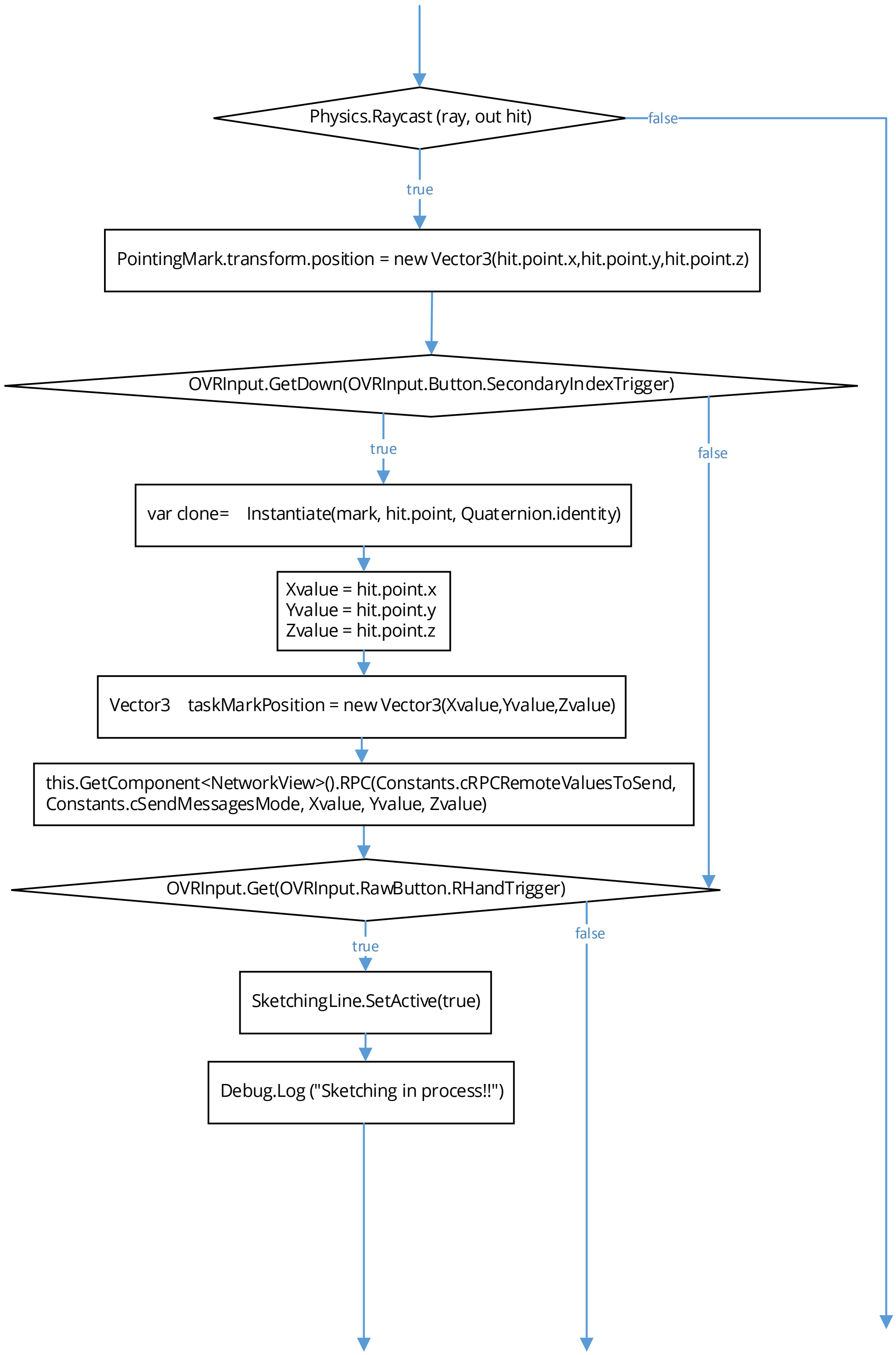


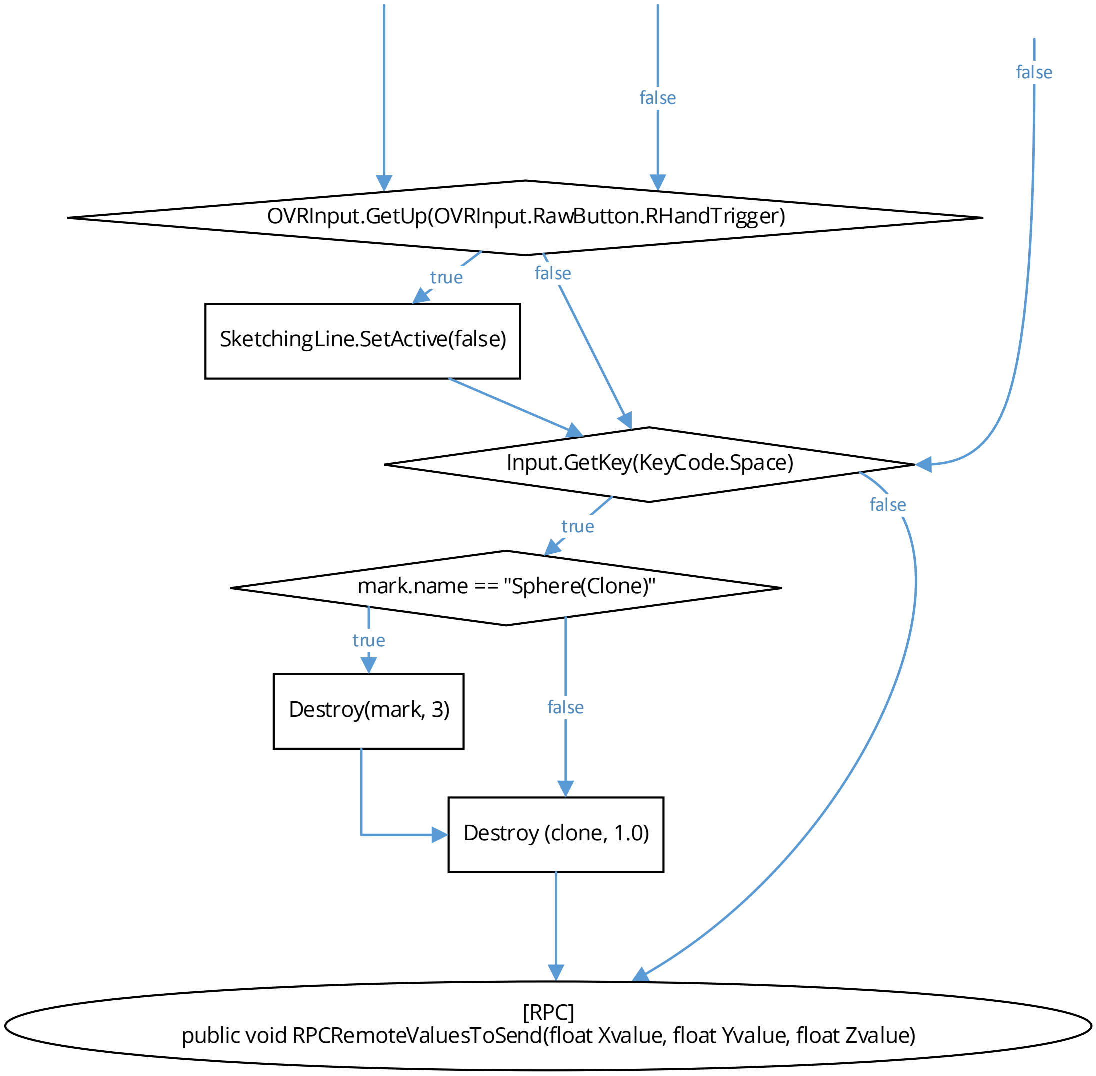

```
/*
 This c# code is for remote sketching and streaming sketching points values.
*/
    using UnityEngine;
    using System.Collections;
    using UnityEngine.UI;
    using System;

    public class RemoteSketchTablet : MonoBehaviour
    {
    public GameObject mark;
    public Transform taskMarkPosition;
    public static float Xvalue;
    public static float Yvalue;
    public static float Zvalue;
    public static float SkthXTblt;
    public static float SkthYTblt;
    public static float SkthZTblt;
    public Transform PointingMark;
```

```
    public GameObject SketchingLine;
    public float time = 100000f;

    void Update () {
        Ray ray = Camera.main.ScreenPointToRay (new Vector3(Input.mousePosition.x,Input.mousePosition.y,Input.mousePosition.z));
        RaycastHit hit;
        if (Physics.Raycast (ray, out hit)) {
            PointingMark.transform.position = new Vector3(hit.point.x,hit.point.y,hit.point.z);
            if (Input.touchCount > 0 && Input.GetTouch (0).phase == TouchPhase.Began)
            {
                var clone=  Instantiate(mark, hit.point, Quaternion.identity);
                Xvalue = hit.point.x;
                Yvalue = hit.point.y;
                Zvalue = hit.point.z;
                Vector3 taskMarkPosition = new Vector3(Xvalue,Yvalue,Zvalue);
                Debug.Log ("The Marked Task Position at: " + taskMarkPosition);
            }

            if (Input.touchCount > 0 && Input.GetTouch (0).phase == TouchPhase.Moved)
            {
                SketchingLine.SetActive(true);
                SkthXTblt=  SketchingLine.transform.position.x;
                SkthYTblt=  SketchingLine.transform.position.y;
                SkthZTblt=  SketchingLine.transform.position.z;
                Debug.Log ("Sketching in process!!!!!");
            }

            if (Input.touchCount > 0 && Input.GetTouch (0).phase == TouchPhase.Ended)
            {
                SketchingLine.SetActive(false);
                Debug.Log ("Sketching in stopped!!!!!");
            }
        }
        if(Input.GetKey(KeyCode.Space))
        {
            SketchingLine.SetActive(null);
        }
    }

public void RemoteSketchTbltValuesToSend(float SkthXTblt, float SkthYTblt, float SkthZTblt)
    {
    }
    }
```

Local and Remote Sketching for IAV module:

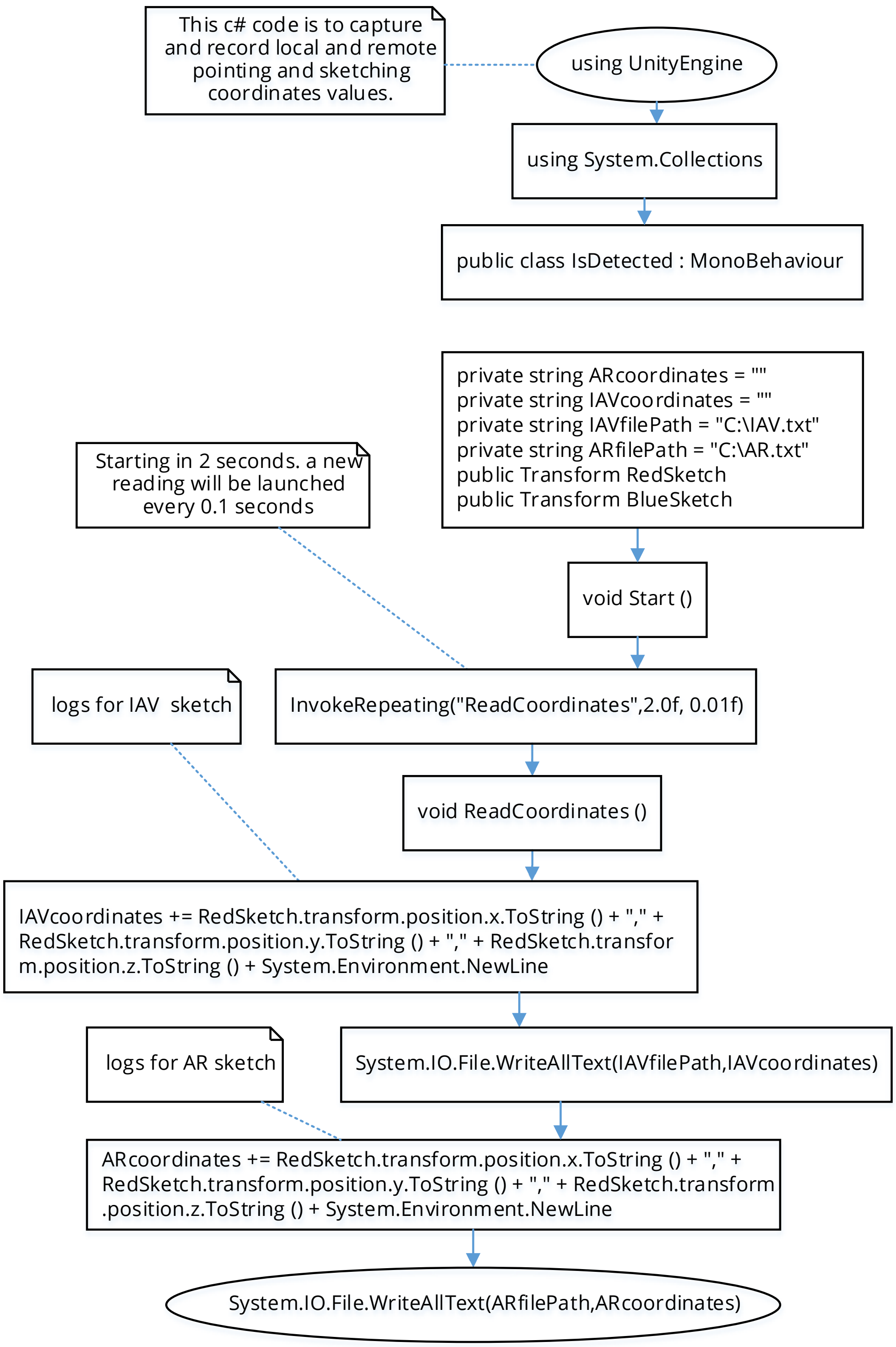



Physics.Raycast (ray, out hit)
false
true
PointingMark.transform.position = new Vector3(hit.point.x,hit.point.y,hit.point.z)
OVRInput.GetDown(OVRInput.Button.SecondaryIndexTrigger)
true
false
var clone= Instantiate(mark, hit.point, Quaternion.identity)
Xvalue = hit.point.x
Yvalue = hit.point.y
Zvalue = hit.point.z
Vector3 taskMarkPosition = new Vector3(Xvalue,Yvalue,Zvalue)
this.GetComponent<NetworkView>().RPC(Constants.cRPCRemoteValuesToSend, Constants.cSendMessagesMode, Xvalue, Yvalue, Zvalue)
OVRInput.Get(OVRInput.RawButton.RHandTrigger)
true
false
SketchingLine.SetActive(true)
Debug.Log ("Sketching in process!!")


false
false
OVRInput.GetUp(OVRInput.RawButton.RHandTrigger)
true
false
SketchingLine.SetActive(false)
Input.GetKey(KeyCode.Space)
true
false
mark.name == "Sphere(Clone)"
true
Destroy(mark, 3)
false
Destroy (clone, 1.0)
[RPC]
public void RPCRemoteValuesToSend(float Xvalue, float Yvalue, float Zvalue)

```
/*
 This c# code is for task marking in the IAV module.
*/
using UnityEngine;
using System.Collections;
using System;

public class TaskMarking : MonoBehaviour {
    public GameObject mark;
    public Transform taskMarkPosition;
    public static float Xvalue;
    public static float Yvalue;
    public static float Zvalue;
    public Transform Righthand;
    public Transform PointingMark;
    public GameObject SketchingLine;
    void Update () {
        Ray ray = new Ray (Righthand.transform.position, Righthand.transform.forward
);
        RaycastHit hit;
    if (Physics.Raycast (ray, out hit)) {
                PointingMark.transform.position = new Vector3(hit.point.x,hit.point.
y,hit.point.z);
            if (OVRInput.GetDown(OVRInput.Button.SecondaryIndexTrigger))
            {
                var clone=  Instantiate(mark, hit.point, Quaternion.identity);
                Xvalue = hit.point.x;
                Yvalue = hit.point.y;
                Zvalue = hit.point.z;
                Vector3 taskMarkPosition = new Vector3(Xvalue,Yvalue,Zvalue);


            }
            if (OVRInput.Get(OVRInput.RawButton.RHandTrigger)) {
                SketchingLine.SetActive(true);
                Debug.Log ("Sketching in process!!");
            }
            if (OVRInput.GetUp(OVRInput.RawButton.RHandTrigger)) {
                SketchingLine.SetActive(false);
                Debug.Log ("Sketching in stopped!!");
            }
                        }
        if(Input.GetKey(KeyCode.Space))
            {
            if(mark.name == "Sphere(Clone)"){
              Destroy(3);
            }
               Destroy (1.0);
            }
    }
    public void RemoteValuesToSend(float Xvalue, float Yvalue, float Zvalue)
    {
    }
}
```

Capture and record local and remote interaction values:



```
/*
 This c# code is to capture and record local and remote pointing and sketching coordinates values.
*/

using UnityEngine;
using System.Collections;

public class IsDetected : MonoBehaviour
{
    private string ARcoordinates = "";
    private string IAVcoordinates = "";
    private string IAVfilePath = "C:\IAV.txt";
    private string ARfilePath = "C:\AR.txt";
    public Transform RedSketch;
    public Transform BlueSketch;

    void Start () {
        // Starting in 2 seconds. a new reading will be launched every 0.1 seconds
        InvokeRepeating("ReadCoordinates",2.0f, 0.01f);
    }
    void ReadCoordinates ()
    {
        // logs for IAV  sketch
        IAVcoordinates += RedSketch.transform.position.x.ToString () + "," + RedSketch.transform.position.y.ToString () + "," + RedSketch.transform.position.z.ToString () + System.Environment.NewLine;
        System.IO.File.WriteAllText(IAVfilePath,IAVcoordinates);
        // logs for AR sketch
        ARcoordinates += RedSketch.transform.position.x.ToString () + "," + RedSketch.transform.position.y.ToString () + "," + RedSketch.transform.position.z.ToString () + System.Environment.NewLine;
        System.IO.File.WriteAllText(ARfilePath,ARcoordinates);
        Debug.Log (IAVcoordinates+"  ||  "+ARcoordinates);
    }
}
```

APPENDIX D: SYSTEM SOFTWARE AND HARDWARE RESOURCES

Tools and Libraries Used in the Prototype System

Tool / Library	Description	Source	Version
Unity3D	Unity Game Engine	http://unity3d.com/	4.1
Vuforia SDK	Vuforia is a cross-platform Augmented Reality (AR) and Mixed Reality (MR) application development platform	https://library.vuforia.com/content/vuforia-library/en/reference/unity/index.html	3.26
Autodesk Revit	3D BIM-based Modeling tool	http://www.autodesk.com/	2013
Autodesk InfraWorks 360	Large-scale Geo-referenced3D modeling tool	http://www.autodesk.com/	2014

System hardware:

Oculus Rift (Oculus, 2016)

Display	
Resolution	960 x 1080 per eye
Refresh Rate	75 Hz, 72 Hz, 60 Hz
Persistence	2 ms, 3 ms
Viewing Optics	
FOV	100° diagonal 94.16° monocular horizontal 95.06° binocular horizontal 106.19° vertical
Interfaces	
Cable	10′ (detachable)
HDMI	Yes
USB Device	Yes
USB Host	USB 2.0 (requires DC Power Adapter)
Positional Tracker USB	USB 2.0
Tracking 6DoF	
Tracking latency	Standard rendering : ~31ms average 4ms game rendering : ~24ms average Timewarp : ~20ms average
Positional tracking	Optical (external IR camera) 752x480 40 IR LEDs Near Infrared CMOS Sensor, 60 Hz
Rotational tracking	Inertial accelerometer/gyroscope/magnetometer 1000Hz
Tracking range	74°x54° 0.4m - 2.5m 72°x52° 0.5m - 2.5m 80°x64°
Precision	0.05mm @ 1.5m 0.05°
Weight	440 grams (without cable)
Included Accessories	HDMI to DVI Adapter DC Power Adapter International Power Plugs Nearsighted lens cups Lens cleaning cloth

Leap Motion Controller (Leap Motion, 2018)

The Leap Motion Controller senses how you naturally move your hands and lets you use your computer in a whole new way. Point, wave, reach, grab. Pick something up and move it. Do things you never dreamed possible. The Leap Motion Controller is sleek, light, and tiny (3" long).

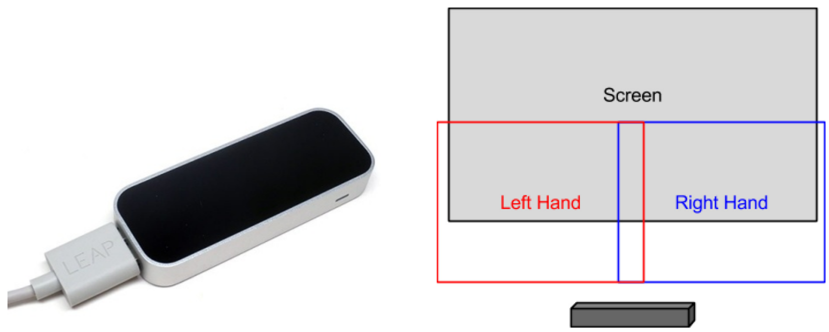


Figure D-1 Leap Motion real space to screen space mappings per hand

Features

- Browse the web, read articles, flip through photos, and play music just by lifting a finger.
- Draw, paint, and design with your fingertip. Users can use a real pencil or paintbrush.
- Slice falling fruit and shoot bad guys with your finger. Steer cars and fly planes with your hands.
- Sculpt, mold, stretch, bend, and build 3D objects. Take things apart and put them back together.
- Reach into the universe, grab the stars, and soar around the sun. It's a whole new way to learn.
- Finger picking

Minimum System Requirements

- Windows 7 or 8 or Mac OS X 10.7
- AMD PhenomTM II or Intel® CoreTM i3 / i5 / i7 Processor
- 2 GB RAM
- USB 2.0 port
- Internet connection

Specifications

- Size: 0.5" (H) x 1.2" (W) x 3" (D)
- Weight: 0.1 pounds

Includes

- Controller
- USB Cables

APPENDIX E: USABILITY TESTING QUESTIONNAIRE RAW DATA

Table E-1 Raw data of the usability testing questionnaire for the AR module

Response	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20
1	2	2	7	1	1	2	1	2	3	2	1	2	1	2	2	2	2	1	2	2
2	2	3	4	1	1	2	4	1	2	2	1	1	1	1	1	2	2	1	2	2
3	2	2	3	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2
4	2	2	5	1	1	1	1	2	3	2	1	1	1	1	1	2	1	2	2	2
5	2	2	2	2	2	2	1	3	3	2	2	2	2	2	2	2	1	2	2	2
6	2	2	3	2	2	2	4	2	2	2	1	1	1	1	1	2	2	1	2	2
7	2	3	1	2	1	2	1	3	3	3	2	2	2	2	2	2	2	2	2	2
8	2	2	2	2	1	2	4	1	1	1	1	1	2	1	2	2	2	1	2	2
9	2	2	1	2	1	2	1	1	1	2	1	1	1	1	2	2	1	1	2	2
10	1	2	7	1	2	2	4	2	2	2	1	2	3	3	3	3	2	2	2	2
11	1	2	5	2	1	1	1	2	2	1	1	2	1	1	2	2	3	1	2	2
12	1	2	6	1	2	2	1	2	2	2	2	2	2	2	2	2	2	3	2	2
13	2	2	4	2	1	2	1	1	1	1	1	2	1	1	1	2	2	3	2	2
14	2	2	5	1	2	1	4	2	2	2	1	2	1	1	1	3	2	2	2	2
15	2	1	5	1	1	2	1	2	2	3	1	1	1	1	1	2	1	2	2	2
16	2	3	7	1	1	2	3	2	2	2	1	1	2	2	2	2	2	2	2	2
17	2	3	5	1	1	2	3	2	2	2	1	2	1	1	1	1	2	1	2	2
18	2	3	5	1	1	1	1	2	2	3	2	2	2	2	2	4	3	2	2	2
19	2	3	6	1	2	1	4	1	1	1	1	2	1	1	1	3	1	2	2	2
20	2	4	7	1	1	2	1	2	2	2	1	2	1	1	1	2	2	2	2	2
21	2	2	6	1	2	2	1	2	1	2	1	2	1	1	1	2	3	1	2	2
22	2	3	6	1	1	1	3	2	1	1	1	1	2	2	2	1	2	1	2	2
23	1	2	6	1	2	2	4	1	1	1	1	1	1	1	2	1	3	2	2	2
24	1	3	7	1	1	2	4	3	3	2	4	4	2	2	1	2	2	2	2	2
25	2	2	5	1	1	2	1	1	1	2	3	4	1	2	2	2	2	2	2	2
26	1	2	5	1	2	2	1	3	2	2	2	1	1	1	2	2	3	2	2	2
27	1	2	6	1	1	1	3	1	1	1	1	1	1	1	1	2	1	1	2	2
28	1	2	7	1	2	2	4	1	1	1	1	4	1	3	2	4	1	1	2	2
29	2	4	7	1	2	1	3	1	1	1	1	1	1	2	1	1	2	1	2	2
30	2	2	6	1	2	2	1	2	2	1	2	2	1	1	1	1	1	1	2	2

Participants after questionnaire comments:

- Having extra information augmented on the exact element can help a lot during inspection and maintenance tasks.
- Discussing a work or a task using remote sketching is very good idea for team collaboration
- It will be nice to have 2D maps overlaid (Augmented)
- I like the virtual hatch. it looked like a real hole in the wall. This was like having an X-ray for the wall. amazing
- It will be much easier and more productive if I can see through AR glasses and use my hands (hands-free)

- Seeing what is behind the wall is very important for installation tasks and this can reduce the errors we make when for example make a cut in the wall and we find pipes or studs, etc. Being able to discuss the tasks visually with a remote colleague is very helpful.
- This is a new experience for me and I found it very interesting to find hidden object without looking to the map and take some measurements.
- Very helpful tool for facility inspection. I was able to see hidden elements and also collaborating with my colleague in a way each one of us knows what the other is doing in real time.
- I like how I was able to see through the wall. It will be awesome if I can use glasses instead of holding the tablet so I can work while seeing both the reality and the virtual objects on it.
- I have three comments: (1) Touch sensitivity is not smooth enough; (2) The whole system is very cool, and I like the part that combines reality with BIM, showing the details behind the surface; and (3) Is it available to give us options for the "a guiding" function? For example, if I want to find maybe a window according to the BIM, then it just guides me to the window I'm finding.
- Honestly, it was fantastic and fascinating. It seems super helpful for facility managers. It makes BIM for facility managers so easier to deal with.
- For visually impaired people, identifying some aspects using the VR glasses presents some challenges without the aid of "our extra pair of eyes". I strongly suggest that this be improved to consider visually impaired people. The sketching accuracy will be variable depending on the ability of the personnel to perform freehand sketch as this is not a gift most people possess. The tagging accuracy of the pointers should also be improved, maybe make them smaller to provide more specific information on the exact element being tagged.
- It was a very nice experience as it was my first time trying VR. I am satisfied with the speed and accuracy.
- Needs some more training to avoid making mistakes.
- It is a little hard for me to handle the device with one hand. The information and instruction are clear and the tasks were easy to do. The accuracy of sketching is not very good, but similar to other devices of the same kind. The accuracy of arrow marking is better than sketching. It is useful to see the structure behind the walls. In short, the experience of using this device is very good.
- All pointing on the screen was considered as arrows, even if it was a button.
- I found the tablet a bit heavy after some time.
- I recommend hand free AR or something that can hold the tablet.

Table E-2 Raw data of the usability testing questionnaire for the IAV module

Response	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20
1	2	2	7	1	1	2	1	3	3	3	2	2	2	2	2	2	2	2	2	3
2	2	3	4	1	1	2	4	2	2	1	1	1	1	1	1	2	2	1	1	2
3	2	2	3	1	1	1	4	1	1	2	1	2	1	2	2	3	2	1	1	2
4	2	2	5	1	1	1	1	2	2	1	1	1	1	2	2	3	3	1	2	1
5	2	2	2	2	2	2	1	2	2	2	1	1	1	1	2	3	2	2	2	2
6	2	2	3	2	2	2	4	2	3	2	2	2	2	2	2	2	1	1	1	1
7	2	3	1	2	1	2	1	2	2	2	2	2	2	2	2	2	2	1	2	2
8	2	2	2	2	1	2	4	2	2	2	1	1	1	1	1	1	1	2	1	1
9	2	2	1	2	1	2	1	1	1	1	1	1	1	1	1	2	2	2	2	2
10	1	2	7	1	2	2	4	3	2	3	1	3	3	2	3	2	2	4	2	4
11	1	2	5	2	1	1	1	2	2	3	1	2	1	1	1	2	2	1	2	2
12	1	2	5	1	2	2	1	3	2	2	2	2	2	2	2	2	2	2	2	3
13	2	2	4	2	1	2	1	1	1	2	1	1	1	1	1	2	1	1	2	2
14	2	2	5	1	2	1	4	2	2	3	1	1	1	1	1	1	2	1	2	3
15	2	1	5	1	1	2	1	1	1	2	1	1	1	1	1	1	1	1	1	1
16	2	3	7	1	1	2	3	2	2	2	1	1	2	2	2	2	2	2	2	2
17	2	3	5	1	1	2	3	2	2	2	1	1	1	1	1	2	1	1	2	2
18	2	3	5	1	1	1	1	2	3	2	1	2	1	1	1	3	2	1	1	1
19	2	3	6	1	2	1	4	2	3	3	2	3	1	1	1	2	3	2	1	2
20	2	4	7	1	1	2	1	2	2	1	2	1	1	1	2	2	1	1	1	2
21	2	2	6	1	2	2	1	2	1	2	2	1	1	1	1	1	1	1	1	1
22	2	3	6	1	1	1	3	1	1	1	2	1	2	3	2	3	3	1	1	1
23	1	2	6	1	2	2	4	1	1	1	1	4	1	1	1	1	1	2	2	2
24	1	3	7	1	1	2	4	3	2	2	4	4	2	2	1	2	3	2	3	2
25	2	2	7	1	1	2	1	2	2	2	4	4	2	3	1	3	2	2	2	2
26	1	2	5	1	2	2	1	2	3	3	1	4	2	2	2	2	1	1	1	3
27	1	2	6	1	1	1	3	2	1	2	1	1	1	3	2	3	1	1	1	3
28	1	2	7	1	2	2	4	1	1	1	2	1	1	1	1	2	1	1	1	1
29	2	4	7	1	2	1	3	1	1	1	1	1	1	1	1	2	2	1	1	2
30	2	2	6	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Participants after questionnaire comments:

- It will be nice to have a search feature. For example, I can write "studs" and it will highlight all the studs.
- The interaction with the remote field worker is very good. It feels like you are there with extra information.
- I needed more training with the controllers.
- Being able to see the remote live video of the real thermostat mapped over the virtual one is pretty accurate. Also, I was amazed by seeing the hidden electrical wires in my view when I used the virtual hatch. Now I can cut the wall with no worries.
- I like the remote visual collaboration with my distant worker. This can reduce the time for waiting for approval and the time for rechecking with happens all the time.

- Referring to the same installed thermostat and sketching around it is a very good technique. It reminds me of a situation when I had to wait for my coworker for about 3 hours just to confirm what I attempted to do at that time. With this tool, he can instantly give his expert advice without coming on site.
- I like that part when I was able to see what's happening with my friend (field worker) through his tablet camera which is matches what I am seeing on the VR. As if we are discussing the object from a different perspective.
- I was surprised how I jumped in a virtual copy of the room I am in. It feels like I was teleported. Being able to communicate with my co-worker remotely with this accuracy differently can save tons of time and avoid the misunderstanding happens during inspection and maintenance.
- It was hard for me to use the controllers.
- I have two comments about system: (1) One controller is enough for all the activities. Maybe it will be better to just use one than two and (2) The IAV experience is very cool. The VR screen resolution is high enough and the user never feel sick while using it for a long time.
- My glasses didn't fit well in the VR headset.
- I think sketching is a skill that is beyond VR.
- Some more training about how to use the controllers can help.
- I have to remove my glasses so that I couldn't see very clearly, and this may cause the accuracy problems. Compared to other systems and devices, the overall accuracy is good. But these kinds of devices and systems I have tried have accuracy problem more or less. It is easy to use the controllers to do the tasks, and the overall instruction is enough.

APPENDIX F: ETHICS AND CONSENT FORMS

SUMMARY PROTOCOL FORM (SPF)

Office of Research – Research Ethics Unit – GM 900 – 514-848-2424 ext. 7481 – oor.ethics@concordia.ca– www.concordia.ca/offices/oor.html

IMPORTANT INFORMATION FOR ALL RESEARCHERS

Please take note of the following before completing this form:

- You must not conduct research involving human participants until you have received your Certification of Ethical Acceptability for Research Involving Human Subjects (Certificate).
- In order to obtain your Certificate, your study must receive approval from the appropriate committee:
  - Faculty research, and student research involving greater than minimal risk is reviewed by the University Human Research Ethics Committee (UHREC).
  - Minimal risk student research is reviewed by the College of Ethics Reviewers (CER; formerly the "Disciplinary College"), except as stated below.
  - Minimal risk student research conducted exclusively for pedagogical purposes is reviewed at the departmental level. **Do not use this form for such research.** Please use the Abbreviated Summary Protocol Form, available on the Office of Research (OOR) website referenced above, and consult with your academic department for review procedures.
- Research funding will not be released until your Certificate has been issued, and any other required certification (e.g. biohazard, radiation safety) has been obtained. For information about your research funding, please consult:
  - Faculty and staff: OOR
  - Graduate students: School of Graduate Studies
  - Undergraduate students: Financial Aid and Awards Office or the Faculty or Department
- Faculty members are encouraged to submit studies for ethics by uploading this form, as well as all supporting documentation, to ConRAD, which can be found in the MyConcordia portal.
- If necessary, faculty members may complete this form and submit it by e-mail tooor.ethics@concordia.ca along with all supporting documentation. Student researchers are asked to submit this form and all supporting documentation by e-mail, except for departmental review. Please note:
  - Handwritten forms will not be accepted.
  - Incomplete or omitted responses may result in delays.
  - This form expands to accommodate your responses.
- Please allow the appropriate amount of time for your study to be reviewed:
  - UHREC reviews greater than minimal risk research when it meets on the second Thursday of each month. You must submit your study 10 days before the meeting where it is to be reviewed. You will normally receive a response within one week of the meeting. Please confirm the deadline and date of the meeting with the staff of the Research Ethics Unit.

- CER reviews, and delegated reviews conducted by UHREC gene require 2 to 4 weeks.

- Research must comply with all applicable laws, regulations, and guidelines, including:
  - The *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans*
  - The policies and guidelines of the funding/award agency
  - The *Official Policies of Concordia University*, including the *Policy for the Ethical Review of Research Involving Human Participants, VPRGS-3*.
- The Certificate is valid for one year. In order to maintain your approval and renew your Certificate, please submit an Annual Report Form one month before the expiry date that appears on the Certificate. You must not conduct research under an expired Certificate.
- Please contact the Manager, Research Ethics at 514-848-2424 ext. 7481if you need more information on the ethics review process or the ethical requirements that apply to your study.

ADDITIONAL INFORMATION FOR STUDENT RESEARCHERS

- If your research is part of your faculty supervisor's research, as approved, please have him or her inform the Research Ethics Unit via e-mail that you will be working on the study.
- If your research is an addition to your faculty supervisor's study, please have him or her submit an amendment request, and any revised documents via e-mail. You must not begin your research until the amendment has been approved.

INSTRUCTIONS FOR COMPLETING THIS FORM

- Please make sure that you are using the most recent version of the SPF by checking the OOR website.
- Please answer each question on the form; if you believe the question is not applicable, enter not applicable.
- Do not alter the questions on this form or delete any material. Where questions are followed by a checklist, please answer by checking the applicable boxes.
- The form can be signed and submitted as follows:
  - Faculty research submitted on ConRAD will be considered as signed as per section 16.
  - SPFs for faculty research submitted via the faculty member's official Concordia e-mail address will also be considered as signed as per section 16.
  - Both faculty and student researchers may submit a scanned pdf of the signature page by e-mail. In this case, the full SPF should also be submitted by e-mail in Word or pdf format (not scanned).
  - If you do not have access to a scanner, the signature page may be submitted on paper to the OOR.

ADDITIONAL DOCUMENTS

Please submit any additional documents as separate files in Word or PDF format.

1. BASIC INFORMATION

Study Title: Collaborative BIM-based Mixed Reality Approach for Supporting Facilities Management Field Tasks

Principal Investigator: Amin Hammad

Principal Investigator's Status:

☒ Concordia faculty or staff

☐ Visiting scholar

☐ Affiliate researcher

☐ Postdoctoral fellow

☐ PhD Student

☐ Master's student

☐ Undergraduate student

☐ Other (please specify):

Type of submission:

☒ New study

☐ Modification or an update of an approved study.
Approved study number (e.g. 30001234):

Where will the research be conducted?

☒ Canada

☐ Another jurisdiction:

2. STUDY TEAM AND CONTACT INFORMATION*

Role	Name	Institution†/ Department / Address‡	Phone #	e-mail address
Principal Investigator	Amin Hammad	EV-7-634	Ext: 5800	hammad@ciise.concordia.ca
Faculty supervisor§				
Committee member‖				
Committee member‖				

Additional Team Members				
Graduate student	Khaled El-Ammari	EV-9-415	Ext:7074	alemmari1@hotmail.com

Notes:
*If additional space is required, please submit a list of team members as a separate document.
†For team members who are external to Concordia only.
‡For individuals based at Concordia, please provide only the building and room number, e.g. GM-910.03.
§For student research only.
|For research conducted by PhD and Master's students only.
°Please include all co-investigators and research assistants.

3. PROJECT AND FUNDING SOURCES

Please list all sources of funds that will be used for the research. Please note that fellowships or scholarships are not considered research funding for the purposes of this section.

Funding Source	Project Title*	Grant Number†	Award Period	
			Start	End

Notes:
* Please provide the project title as it appears on the Notice of Award or equivalent documentation.
† If you have applied for funding, and the decision is still pending, please enter "applied".

4. OTHER CERTIFICATION REQUIREMENTS

Does the research involve any of the following (check all that apply):

☐ Controlled goods or technology

☐ Hazardous materials or explosives

☐ Biohazardous materials

☐ Human biological specimens

☐ Radioisotopes, lasers, x-ray equipment or magnetic fields

☐ Protected acts (requiring professional certification)

☐ A medical intervention, healthcare intervention or invasive procedures

Please submit any certification or authorization documents that may be relevant to ethics review for research involving human participants.

5. LAY SUMMARY

Instead of using traditional methods in facilities management everyday practice, this research investigates how field tasks (such as inspection) can be improved by using advanced technologies such as Mixed Reality.

6. RISK LEVEL AND SCHOLARLY REVIEW

As part of the research, will participants be exposed to risk that is greater than minimal?

Minimal risk means that the probability and magnitude of the risks are greater than those to which participants would be exposed in those aspects of their daily lives that are pertinent to the research.

☐ Yes

☒ No

However, Mixed Reality devices can generate discomfort to the user.

Has this research received favorable review for scholarly merit?

Scholarly review is not required for minimal risk research.

For faculty research, funding from a granting agency such as CIHR, FQRSC, or CINQ is considered evidence of such review. Please provide the name of the agency.

For student research, a successful defense of a thesis or dissertation proposal is considered evidence of such review. Please provide the date of your proposal defense.

☒ Yes *PhD research proposal was accepted on* 6/6/2016

☐ No

☐ Not required

If you answered no, please submit a Scholarly Review Form, available on the OOR website. For studies to be conducted at the PERFORM Centre, please submit the Scientific Review Evaluator Worksheet.

7. RESEARCH PARTICIPANTS

Will any of the participants be part of the following categories?

☐ Minors (individuals under 18 years old)

☐ Individuals with diminished mental capacity

☐ Individuals with diminished physical capacity

☐ Members of Canada's First Nations, Inuit, or Métis peoples

☐ Vulnerable individuals or groups(vulnerability may be caused by limited capacity, or limited access to social goods, such as rights, opportunities and power, and includes individuals or groups whose situation or circumstances make them vulnerable in the context of the research project, or those who live with relatively high levels of risk on a daily basis)

a) Please describe potential participants, including any inclusion or exclusion criteria.

Students, Professors, and workers at the Facilities Management Department of Concordia University.

b)Please describe in detail how potential participants will be identified, and invited to participate. Please submit any recruitment materials to be used, for example, advertisements or letters to participants.

We will coordinate with the Facilities Management Department of Concordia University to identify the participants. Also, grad students at building engineering (BCEE department) will be invited.

c) Please describe in detail what participants will be asked to do as part of the research, and any procedures they will be asked to undergo. Please submit any instruments to be used to gather data, for example questionnaires or interview guides.

The invited participates will be asked to hold a tablet PC and perform four simplified facility management inspection tasks. They will be using Augmented Reality application that allows them to perform these tasks. After conducting the test and measuring the time it took for each task, he/she will be asked to answer questions about his/her experience using the system. The expected time to perform and fill the questionnaire in 20 min.

d) Do any of the research procedures require special training, such as medical procedures or conducting interviews on sensitive topics or with vulnerable populations? If so, please indicate who will conduct the procedures and what their qualifications are.

No.

8. INFORMED CONSENT

a) Please explain how you will solicit informed consent from potential participants. Please submit your written consent form. In certain circumstances, oral consent may be appropriate. If you intend to use an oral consent procedure, please submit a consent script containing the same elements as the template, and describe how consent will be documented.

Please note: written consent forms and oral consent scripts should follow the consent form template available on the OOR website. Please include all of the information shown in the sample, adapting it as necessary for your research.

Please see attached consent form.

b) Does your research involve individuals belonging to cultural traditions in which individualized consent may not be appropriate, or in which additional consent, such as group consent or consent from community leaders, may be required? If so, please describe the appropriate format of consent, and how you will solicit it.

No.

9. DECEPTION

Does your research involve any form of deception of participants? If so, please describe the deception, explain why the deception is necessary, and explain how participants will be de-briefed at the end of their participation. If applicable, please submit a debriefing script.

Please note that deception includes giving participants false information, withholding relevant information, and providing information designed to mislead.

No.

10. PARTICIPANT WITHDRAWAL

a) Please explain how participants will be informed that they are free to discontinue at any time, and describe any limitations on this freedom that may result from the nature of the research.

Please see the consent form.

b) Please explain what will happen to the information obtained from a participant if he or she withdraws. For example, will their information be destroyed or excluded from analysis if the participant requests it? Please describe any limits on withdrawing a participant's data, such as a deadline related to publishing data.

If the participant withdraw, His/her information **will be disposed**.

As mentioned in the consent form, the time limit on withdrawing a participant's data is **January 30, 2018**.

11. RISKS AND BENEFITS

a) Please identify any foreseeable benefits to participants.

No benefits.

b) Please identify any foreseeable risks to participants, including any physical or psychological discomfort, and risks to their relationships with others, or to their financial well-being.

There is no risk for you participating in this research. However, Mixed Reality devices can generate discomfort to the user. That is due to the mismatching that may happen between the user head movement and the rendered scene. Sometimes, the computer cannot update the scene in real time, therefore very quick movement of the user could possibly lead to motion sickness or dizziness. To decrease these chances from happening, we used high-performance Graphics Processing Unit (GPU).

c) Please describe how the risks identified above will be minimized. For example, if individuals who are particularly susceptible to these risks will be excluded from participating, please describe how they will be identified. Furthermore, if there is a chance that researchers will discontinue participants' involvement for their own well-being, please state the criteria that will be used.

There are no risks.

d) Please describe how you will manage the situation if the risks described above are realized. For example, if referrals to appropriate resources are available, please provide a list. If there is a chance that participants will need first aid or medical attention, please describe what arrangements have been made.

There are no risks.

12. REPORTABLE SITUATIONS AND INCIDENTAL FINDINGS

a) Is there a chance that the research might reveal a situation that would have to be reported to appropriate authorities, such as child abuse or an imminent threat of serious harm to specific individuals? If so, please describe the situation, and how it would be handled.

There is no such chance.

Please note that legal requirements apply in such situations. It is the researcher's responsibility to be familiar with the laws in force in the jurisdiction where the research is being conducted.

b) Is there a chance that the research might reveal a material incidental finding? If so, please describe how it would be handled.

There is no such chance.

Please note that a material incidental finding is an unanticipated discovery made in the course of research but that is outside the scope of the research, such as a previously undiagnosed medical or psychiatric condition that has significant welfare implications for the participant or others.

13. CONFIDENTIALITY, ACCESS, AND STORAGE

a) Please describe the path of your data from collection to storage to its eventual archiving or disposal, including details on short and long-term storage (format, duration, and location), measures taken to prevent unauthorized access, who will have access, and final destination (including archiving, or destruction).

The data will be stored on a password-protected computer accessible only by Principal Investigator (Dr. Amin Hammad) and PhD student (Khaled El Ammari) for a period of one year.

☒	Anonymous	The information provided never had identifiers associated with it, and the risk of identification of individuals is low, or very low.
☐	Anonymous results, but identify who participated	The information provided never had identifiers associated with it. The research team knows participants' identity, but it would be impossible to link the information provided to link the participant's identity.
☐	Pseudonym	Information provided will be linked to an individual, but that individual will only provide a fictitious name. The research team will not know the real identity of the participant.
☐	Coded	Direct identifiers will be removed and replaced with a code on the information provided. Only specific individuals have access to the code, meaning that they can re-identify the participant if necessary.
☐	Indirectly identified	The information provided is not associated with direct identifiers (such as the participant's name), but it is associated with information that can reasonably be expected to identify an individual through a combination of indirect identifiers (such as place of residence, or unique personal characteristics).
☐	Confidential	The research team will know the participants' real identity, but it will not be disclosed.
☐	Disclosed	The research team will know the participants' real identity, and it will be revealed in accordance with their consent.
☐	Participant Choice	Participants will be able to choose which level of disclosure they wish for their real identity.
☐	Other (please describe)	

b) Please identify the access that the research team will have to participants' identity:

c) Please describe what access research participants will have to study results, and any debriefing information that will be provided to participants' post-participation.

The participants will be informed about the results of the research (i.e. research report) if they wish.

d) Would the revelation of participants' identity be particularly sensitive, for example, because they belong to a stigmatized group? If so, please describe any special measures that you will take to respect the wishes of your participants regarding the disclosure of their identity.

No.

e) In some research traditions, such as action research, and research of a socio-political nature, there can be concerns about giving participant groups a "voice". This is especially the case with groups that have been oppressed or whose views have been suppressed in their cultural location. If these concerns are relevant for your participant group, please describe how you will address them in your project.

These concerns are not relevant for our participant group.

14. MULTI-JURISDICTIONAL RESEARCH

Does your research involve researchers affiliated with an institution other than Concordia? If so, please complete the following table, including the Concordia researcher's role and activities to be conducted at Concordia. If researchers have multiple institutional affiliations, please include a line for each institution.

No.

Researcher's Name	Institutional Affiliation	Role in the research (e.g. principal investigator, co-investigator, collaborator)	What research activities will be conducted at each institution?

15. ADDITIONAL ISSUES

Bearing in mind the ethical guidelines of your academic or professional association, please comment on any other ethical concerns which may arise in the conduct of this research. For example, are there responsibilities to participants beyond the purposes of this study?

No.

16. DECLARATION AND SIGNATURE

Study Title: **Collaborative BIM-based Mixed Reality Approach for Supporting Facilities Management Field Tasks**

I hereby declare that this Summary Protocol Form accurately describes the research project or scholarly activity that I plan to conduct. I will submit a detailed modification request if I wish to make modifications to this research.

I agree to conduct all activities conducted in relation to the research described in this form in compliance with all applicable laws, regulations, and guidelines, including:

- The *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans*
- The policies and guidelines of the funding/award agency
- The *Official Policies of Concordia University*, including the *Policy for the Ethical Review of Research Involving Human Participants, VPRGS-3*.

Principal Investigator Signature**:** ______________________________
Date: ______________________________

FACULTY SUPERVISOR STATEMENT (REQUIRED FOR STUDENT PRINCIPAL INVESTIGATORS):

I have read and approved this project. I affirm that it has received the appropriate academic approval, and that the student investigator is aware of the applicable policies and procedures governing the ethical conduct of human participant research at Concordia University. I agree to provide all necessary supervision to the student. I allow release of my nominative information as required by these policies and procedures in relation to this project.

Faculty Supervisor Signature: ______________________________
Date: ______________________________

INFORMATION AND CONSENT FORM

Study Title: Collaborative BIM-based Mixed Reality Approach for Supporting Facilities Management Field Tasks

Researcher: Khaled El Ammari

Researcher's Contact Information:

1515 Ste-Catherine Street West, EV9.215
Montréal, Québec, H3G 2W1, Canada
Phone: (514) 848-2424 ext: 7074
Email: elamm_k@encs.concordia.ca

Faculty Supervisor: Dr. Amin Hammad

Faculty Supervisor's Contact Information:

1515 Ste-Catherine Street West, EV7.634
Montréal, Québec, H3G 2W1, Canada
Phone: (514) 848-2424 ext: 5800
Email: hammad@ciise.concordia.ca

Source of funding for the study:

You are being invited to participate voluntarily in the research study mentioned above. This form provides information about what participating would mean. Please read it carefully before deciding if you want to participate or not. If there is anything you do not understand, or if you want more information, please ask the researcher.

A. PURPOSE

The purpose of the research is to study the effect of using Augmented Reality (AR) based facility management system with and without navigation visual support and collaboration from the remote office.

B. PROCEDURES

You will be asked to hold a tablet and perform four simplified facility management tasks. After performing the test and measuring the time it took for each task, you will be asked to answer questions about your experience using the system. The expected time to perform and fill the questionnaire in 20 min.

C. RISKS AND BENEFITS

There is no risk for you participating in this research. However, Mixed Reality devices can generate discomfort to the user. That is due to the mismatching that may happen between the user head movement and the rendered scene. Sometimes, the computer cannot update the scene in real time, therefore very quick movement of the user could possibly lead to motion sickness or dizziness. To decrease these chances from happening, we used high-performance Graphics Processing Unit (GPU).
This research is not intended to be used for personal benefit and it is only for academic purposes.

D. CONFIDENTIALITY

The usability testing and the survey will be performed in our research lab EV 9.415 at SGW campus. We intend to publish the results of the research. However, it will not be possible to identify any participant in the published results. All personal information collected by the questionnaire are confidential and it will not be published or accessed by anyone. Furthermore, the information gathered will be anonymous. That means that it will not be possible to make a link between the participant and the information he/she provided. We will destroy the information five years after the end of the study.

F. CONDITIONS OF PARTICIPATION

You do not have to participate in this research. It is purely your decision. You can stop at any time. You can also ask that the information you provided not be used, and your choice will be respected and your collected data will be disposed.

If you decide that you don't want us to use your information, you must tell the researcher before January 30, 2018. There are no negative consequences for not participating, stopping in the middle, or asking us not to use your information.

G. PARTICIPANT'S DECLARATION

I have read and understood this form. I have had the chance to ask questions and any questions have been answered. I agree to participate in this research under the conditions described.

NAME (please print) ____
SIGNATURE ____
DATE ____

If you have questions about the scientific or scholarly aspects of this research, please contact the researcher. His contact information is on page 1. You may also contact their faculty supervisor.
If you have concerns about ethical issues in this research, please contact the Manager, Research Ethics, Concordia University, 514.848.2424 ex. 7481 or oor.ethics@concordia.ca.

APPENDIX G: CMMSS AND THEIR MAIN FUNCTIONALITIES

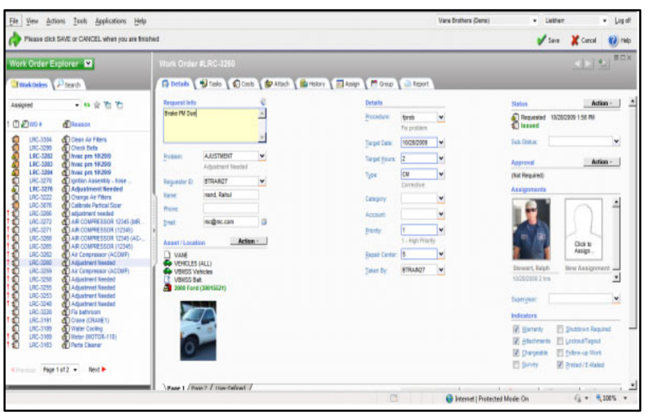
CMMS is software that is used to schedule and record operation and preventive/planned maintenance activities associated with facility equipment. The CMMS can generate and prioritize work orders and schedules for staff to support "trouble" calls and to perform periodic/planned equipment maintenance. Upon completion of a work order, performance information, such as the date work was performed, supplies/inventory, and man-hours expended, typically is loaded into the database for tracking, to support future operations/planning. In addition, it is important not to confuse CMMS with a Computer-Aided Facilities Management (CAFM) system, consider a patient room in a hospital, e.g., ensuring that the Nurse Call System in the room is "properly inspected, maintained, and repaired" is a CMMS activity. "Knowledge" about the medical department staff; specific patient in the room; the room's contents (phones, TVs, beds–including whether they are moved from room-to-room); and equipment hook-ups (electrical, oxygen, communications, etc.) relate to CAFM activities. CMMS and CAFM systems continue to merge into Integrated Work Order Management Systems (IWOMS).

CMMS are used by facilities maintenance organizations to record, manage, and communicate their day-to-day operations. The system can provide reports used in managing the organization's resources, preparing facilities key performance indicators (KPIs)/metrics to use in evaluating the effectiveness of the current operations, and for making organizational and personnel decisions. In today's maintenance world, the CMMS is an essential tool for recording work requirements, tracking the status of the work, and analyzing the recorded data in order to manage the work, produce reports, and help control costs. Facility professionals use tools to manage the planning and day-to-day operations and maintenance activities required for a single facility or a large complex. These tools also provide all of the information required to manage the work, the workforce, and the costs necessary to generate management reports and historical data.

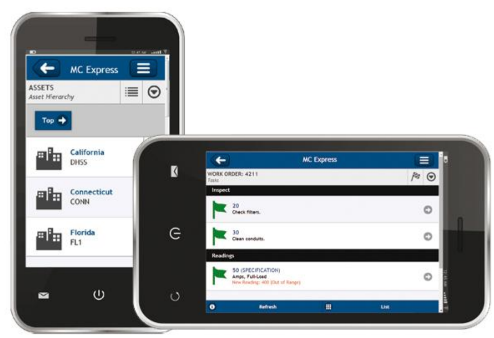
Maintenance Connection:

Maintenance Connection (MaintenanceConnection 2017) is a web-based software for maintenance management. It is targeted at organizations in general FM, healthcare, manufacturing, government, utilities, warehouses, energy development, travel agencies, and other specialized industries. Furthermore, the system optimizes lifecycles of assets, tracks and manages maintenance costs, provides insight on possible equipment failures, streamlines labor efforts, and performs other crucial tasks for meeting the full potential of maintenance and FM.

The software is web-based with integration capabilities which can be hosted either online or on the customer's work site. The system runs on the Microsoft SQL Server relational database engine. In addition, the software is designed to readily integrate with other systems, such as enterprise resource planning software and CAD-based FM Software. The homepage for each user is tailored according to the role within the organization, allowing for maximum efficiency when any given employee logs in. To direct the user to the most pressing issues, work orders assignments, requests, and other objectives that need immediate attention are highlighted in red to avoid accidental neglect.



(a) Work Order details



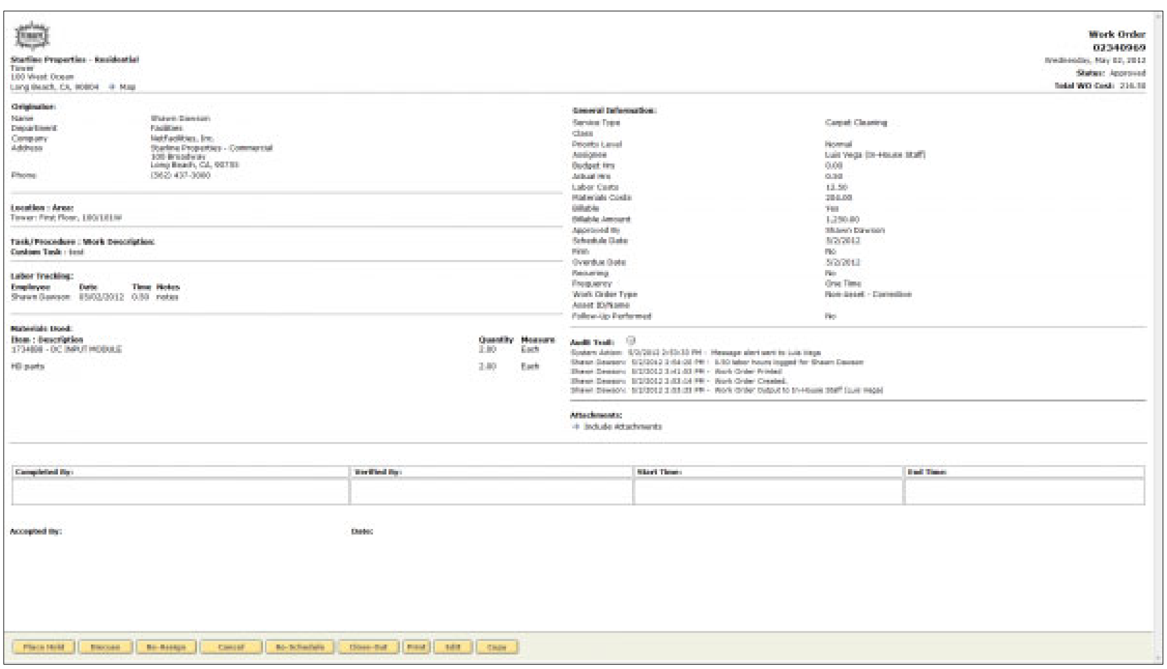
(b) MC Express - Mobile tablet screenshot

Figure G-1 Maintenance Connection user interfaces MaintenanceConnection 2017

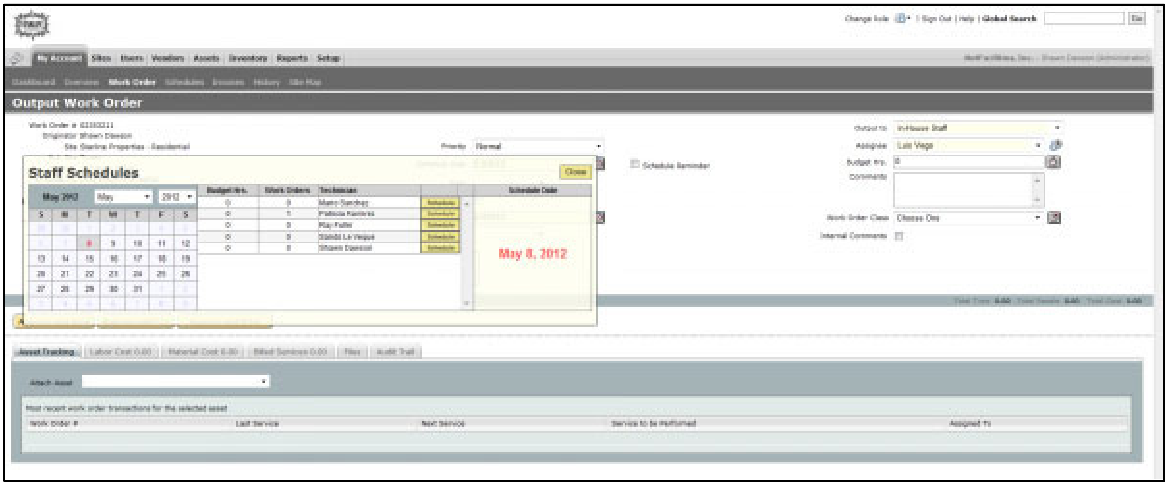
NetFacilities Software:

NetFacilities (NetFacilities, 2018) offers comprehensive online CMMS tools that helps organizations manage their facilities. From work orders to grounds management, assets to inventory control, NetFacilities brings together team, sites and assets into a single web-based system with mobile capabilities that allow users to track and manage work orders from the field.

NetFacilities serves wide variety of facilities ranging from residential and educational facilities to industrial and transportation facilities. However, the software pricing varies based on the number of sites and jobs being tracked. The software increases an organization's ability to manage aspects of maintenance including preventive and predictive maintenance. By linking together all sites, buildings, staff and vendors into a single network, facility managers can streamline and optimize workflow, increasing collaboration across all departments while also tracking costs and monitoring performance. In addition to work order, asset and inventory management, NetFacilities also provides customizable reporting that allow managers to analyze labor costs, productivity, repair costs.



(a) Submit Work Order



(b) Output Work Order

Figure G-2 NetFacilities user interfaces

Maximo by IBM:

Maximo asset management by IBM (IBM, 2016) combines asset management with maintenance management. It includes a full suite of tools, including asset and inventory management, predictive and preventive maintenance, and work order management. Using Maximo allows companies to monitor and manage the full lifecycle of their enterprise assets, including facilities, communications, transportation, production, and infrastructure. The software centralized functionality ensures that users have visibility and control of asset conditions and processes while increasing productivity and lowering downtime. Moreover, the software is deployable on the cloud and or on-premise and is accessible from almost any device.

Maximo extension for BIM provides the ability to leverage BIM data within Maximo. This includes support for importing/updating BIM data, export from Maximo, and full 3D display of BIM data in context with Maximo applications and processes. To support interoperability and visualization, the Maximo 3D Viewer integrates with Autodesk BIM360 viewer and Navisworks on installation, and IBM's Maximo 3D Viewer API allows for potential integration with other third-party viewers. Figure D-3showsthe integrated Maximo 3D Viewer with work order tracking.

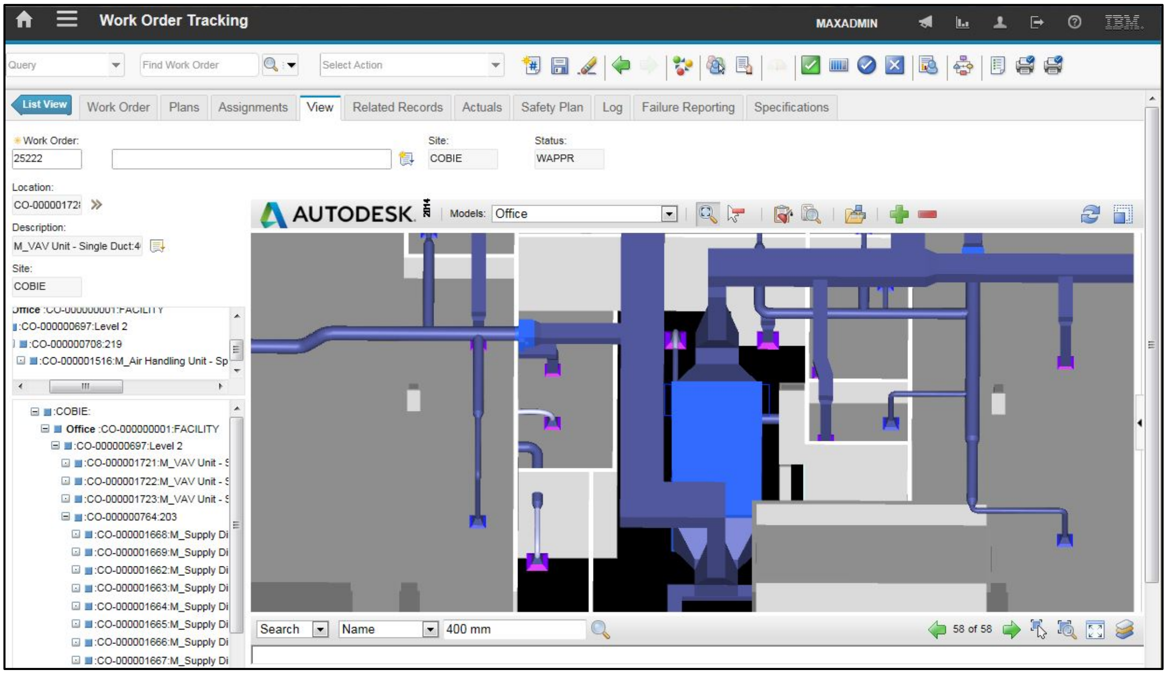


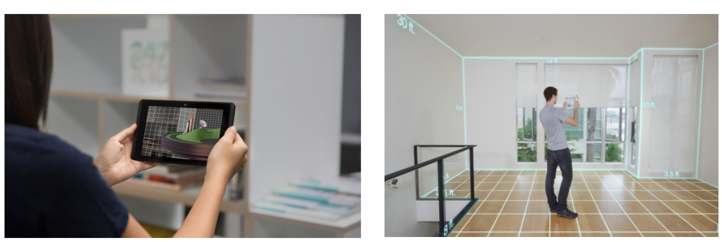
Figure G-3 3D Viewer integrated with work order tracking

APPENDIX H: REVIEW OF MR-BASED TECHNOLOGIES

In the past five years, MR technologies became more attractive for many industries such as the gaming and entertainment industry. Giant IT companies such as Facebook and Google saw the potential of investing in such promising technologies. For example, Facebook is developing the *Oculus Rift* VR headset.

Project Tango, shown in Figure H-1(a), is a Google technology platform, which was originally developed by a team led by computer scientist Johnny Lee (Google, 2016). Project Tango is a prototype phone containing highly customized software and hardware designed to allow the tracking its motion in full 3D in real-time (Keralia et al., 2014). The mobile platform uses CV to enable tablets to detect their position relative to the world around them without using external signals (e.g., GPS). The core technologies in the *Project Tango* are motion tracking, area learning, and depth perception. This allows application developers to create user experiences that include indoor navigation, 3D mapping, and measurement of physical spaces, implemented using AR and VR environments. The SDK provides an interface to integrate with Unity game engine and provides also java and C Application Programming Interfaces (APIs).

The *Structure Sensor* shown in Figure H-1(b) is a small sensor that can be attached on an iPad and offers 3D scanning and mapping for the objects and masses. This allows an accurate depth analysis and spatial restructuring of VR environments. The sensor is capable of providing accurate textured 3D objects scanning and 360-degree views. The Structure SDK provides developers with a stable framework for creating iOS applications in Xcode, which leverage the CV techniques. It also comes with a plug-in for game engines including Unity. The sensor utilizes the 6-DoF positional tracking to control the 3D user's point of view in the VEs.



(a) Project Tango tablet (Google PT, 2016)   (b) Structure Sensor technology (STio, 2016)

Figure H-1 Google Project Tango and Structure Sensor technologies

Interaction in both VR and AR environments is important to develop interactive experiences that are meaningful to the users. Billinghurst et al. (2009) developed several interaction methods and technologies MR applications. However, gadget-free interactivity seems to be an attractive choice especially for immersive VR applications. *Leap Motion controller* (Leap Motion, 2018) is a small computer USB device sensor that supports hand and finger motions tracking as input. The controller is designed to be physically placed on a desktop, facing upward or on a HMD, facing forward. Using its two monochromatic IR cameras and its three infrared Light-Emitting Diode (LEDs), the controller observes a roughly hemispherical area above the device to a distance of 60 cm (Colgan, 2014). The tracked motions can be replicated in the VR environments using rigged detailed hands. This hardware allows VR users to replicate their hands and fingers movements in the VR environment in a meaningful interactive way. This interaction can be useful in immersive environments where the user is visually detached from his physical environment. The controller has an API to integrate with popular game engines such as Unity3D and Unreal to develop an interactive VR games.

Effective human-computer interaction (HCI) is strongly influenced by input devices, which sense the physical interaction of users. There is a large variety of classical input devices, e.g., mouse, trackball, joystick, touch pad or touch screen. Besides the classical input devices, there are more and more contact-free input systems available, e.g., gesture-recognition, eye-gaze control or speech input. Figure H-2 shows gesture-based *Leap Motion Controller* with the coordinate system.

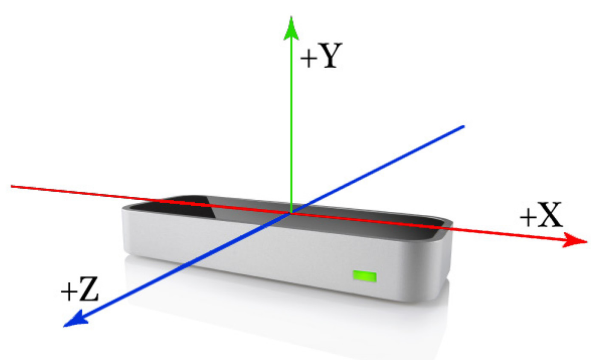


Figure H-2 Leap Motion controller with the coordinate system (Leap motion, 2018)