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The University of Osaka

Doctoral Thesis

**Development of a Mixed Reality System
for Indoor Environmental Renovation
Integrated with Computational Fluid
Dynamics, 360-Degree Streaming, and
Deep Learning**

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January 2024

Graduate School of Engineering,
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Division of Sustainable Energy and Environmental Engineering

博士論文

数値流体力学と 360 度ストリーミング
と深層学習を統合した室内環境改修の
ための複合現実感システムの開発

学籍番号 28H18807

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Abstract

In advanced societies, the renovation of existing building stock has become a vital area of study, holding significant social, economic, and environmental value. With an increasing trend in stock renovation, there is a high demand for innovative methods that give new life to existing building stock, promoting sustainable practices over new constructions as opposed to building new ones. This study introduces an integrated system that merges Computational Fluid Dynamics (CFD), Mixed Reality (MR), Building Information Modeling (BIM), and Generative Adversarial Networks (GANs) for a comprehensive approach to stock renovation.

The system facilitates a collaborative design process, involving both professionals and non-professional stakeholders, enhancing the participatory aspect of design. Integrating BIM models into an MR environment provides a realistic and interactive platform for visualizing design plans. Users, equipped with head-mounted displays (HMDs), can interact in a shared MR space, manipulating virtual structures and objects through gestures and simple voice commands, leading to a more intuitive understanding of design intentions and a more efficient evaluation of renovation proposals.

The CFD results within the system allow for the simulation of indoor thermal environments, taking into account daylight and ventilation effects, and ensuring a healthy, comfortable, and energy-efficient indoor space. The MR component not only visualizes these simulations but also provides an intuitive interface for real time feedback and evaluation of different renovation scenarios, enhancing the decision-making process for all stakeholders involved. In addition, a new CFD animation generation method for the MR system is proposed that allows users to consider the entirety of changes in the thermal environment.

Furthermore, the system employs GANs method to generate interior renovation drawings, tailored to user preferences and designer styles. During the early stage of

renovation design, establishing prompt feedback is vital to unite all stakeholders. An overall cognition of the proposed renovation plans will contribute to a better renovation design. This integration of GANs results and Diminished Reality (DR) methods into the MR environments transforms 2D drawings into immersive experiences, providing the visualization and presentation of renovation plans. The system also includes full-reference image quality assessment (FR-IQA) methods to evaluate the quality of GANs generated images, ensuring that the visual output meets the required standards.

In conclusion, this dissertation presents a prototype of an integrated Co-Designing system, connecting multiple HMDs in a local area network (LAN), providing a comprehensive, interactive, and user-friendly tool for stock renovation. The system not only supports the design and evaluation of biophilic indoor environments but also encourages occupant participation, ensuring that the renovated spaces meet the needs and preferences of all users, contributing to the overall well-being and comfort of the occupants.

Keywords: Thermal Environment, Computational Fluid Dynamics (CFD), Renovation design, Mixed Reality (MR), Diminished Reality (DR), Generative Adversarial Networks (GANs), Co-Designing

Preface

This dissertation is the original work by Yuehan Zhu under the supervision of Assoc. Prof. Tomohiro Fukuda. Two journal articles and three international conference proceedings that relate to this dissertation have been submitted or published and are listed below.

Journal articles:

1. Zhu, Y., Fukuda, T., & Yabuki, N. (2019). Integrating Animated Computational Fluid Dynamics into Mixed Reality for Building-Renovation Design. *Technologies*, 8(1), 4. <https://doi.org/10.3390/technologies8010004>
2. Zhu, Y., Fukuda, T., & Yabuki, N. (2024). A Mixed Reality Design System for Interior Renovation: Inpainting with 360-Degree Live Streaming and Generative Adversarial Networks after Removal. *Technologies*, 12(1), 9. <https://doi.org/10.3390/technologies12010009>

International conference proceedings:

1. Zhu, Y., Fukuda, T., & Yabuki, N. (2018, May). SLAM-Based MR with Animated CFD for Building Design Simulation. *In Proceedings of the 23rd International Conference of the Association for Computed-Aided Architectural Design Research in Asia (CAADRIA)*, Tsinghua University, School of Architecture, Beijing, China (pp. 17-19). <https://doi.org/10.52842/conf.caadria.2018.1.391>
2. Zhu, Y., Fukuda, T., & Yabuki, N. (2019, April). Synthesizing 360-Degree Live Streaming for an Erased Background to Study Renovation Using Mixed Reality. *In Proceedings of the 24th International Conference of the Association for Computed-Aided Architectural Design Research in Asia (CAADRIA)*, Victoria

University of Wellington, Faculty of Architecture & Design (pp. 71-80).
<https://doi.org/10.52842/conf.caadria.2019.2.071>

3. Zhu, Y., Fukuda, T., & Yabuki, N. (2020). Integrated Co-Designing Using Building Information Modeling and Mixed Reality with Erased Backgrounds for Stock Renovation. *Ecaade 2020: Anthropologic—Architecture and Fabrication in the Cognitive Age*, 1, 153-160. <https://doi.org/10.52842/conf.ecaade.2020.1.153>

Acknowledgment

In 2015, fresh out of college, I set foot in the university that had long captured my imagination—Osaka University. Joining the Yabuki Laboratory as a research student, I juggled exam preparations while actively participating in various lab activities. The daily life in the lab was rich and fulfilling, particularly memorable were the Open Lab days, which left a lasting impression on me. On those days, the lab was bustling with visitors, eager to explore and experience our work. Despite printing several batches of posters, we always seemed to run out. This experience made me realize that like myself, many were drawn to the exceptional research quality and fascinating topics pursued at the university.

In 2016, I officially became a Master's student at Yabuki Laboratory. It was also at that time that I met my life mentor, Associate Professor Tomohiro Fukuda, as well as Professor Nobuyoshi Yabuki, who has been quietly supporting me all along. Over the next two years, with their guidance, I participated in numerous conferences, from local academic gatherings to international symposiums. In 2018, I was honored with the Young CAADRIA Award—a highlight of my life that I will forever cherish. I am deeply grateful to Prof. Yabuki for his unwavering support, constantly striving to enhance our English proficiency and ensuring our successful presentations at international conferences. My heartfelt thanks go to A.P. Fukuda, who patiently revised papers with me, mentored me through research tours, and provided unwavering support. I would also like to extend my gratitude to Mr. Yokoi for his meticulous guidance on using OpenFOAM, to Mr. Inoue for staying up all night with me to work on our paper, to Mr. Cao for his assistance in daily life, and to Mr. Ding, Dr. Chen, Mr. Wang, Mr. Yamazaki, Dr. Hitaka, Ms. Yan, Ms. Han, Mr. Nishimura, Dr. Chavanont, Dr. Natthapol, Dr. Motamedi, Mr. Yamamoto, and many others for the wonderful memories created together.

In 2018, I progressed to the doctoral program, continuing my research at the Yabuki Laboratory. That same year, I experienced my first earthquake, an M_j 6.1 quake. Asleep at the time, I awoke to the impact of my monitor hitting my pillow, and faced my first profound encounter with life's fragility. In the following years, the world fought with the COVID-19 pandemic. Stranded in China during the Spring Festival, I watched as hospitals reached capacity, people died and cities went into lockdown, and once again, I was gripped by a sense of apprehension. Perhaps it was this shift in mindset that led to a slowdown in my research progress. Nevertheless, A.P. Fukuda remained steadfast in his support, caring for both my academic and personal well-being. When he learned of my depressive state, he treated me to authentic Chinese cuisine, lifted my spirits, and even planned outings to help me unwind. Words cannot express my gratitude to him. Prof. Yabuki, too, showed great understanding, never pressuring me even as I took numerous leaves of absence, and continuously guiding my studies with patience. I would also like to thank Prof. Kondo and Prof. Kii for guiding my thesis and suggesting many meaningful comments for revision. In addition to my mentors, I am thankful to Mr. Ishikawa for the academic exchanges, Mr. Ikeno for sharing my hobbies and interests, and my three doctoral friends, Dr. Xia, Dr. Zhang, and Dr. Li, for their unwavering support in both research and daily life. It is with everyone's strength that I have been able to come this far.

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List of Abbreviations

Abbreviation	Meaning
3D	Three-Dimensional
AR	Augmented Reality
BIM	Building Information Modeling
CAVE	Cave Automatic Virtual Environment
CFD	Computational Fluid Dynamics
CG	Computer Graphics
DR	Diminished Reality
FFD	Fast Fluid Dynamics
FR-IQA	Full-Reference Image Quality Assessment
GANs	Generative Adversarial Networks
GPS	Global Positioning System
GPU	Graphics Processing Unit
HMDs	Head-Mounted Displays
IoU	Intersection over Union
LAN	Local Area Network
MR	Mixed Reality
PC	Personal Computer
PSNR	Peak Signal-to-Noise Ratio
SLAM	Simultaneous Localization And Mapping
SSIM	Structural Similarity Index Measure
UWP	Universal Windows Platform

VR	Virtual Reality
VRML	Virtual Reality Modeling Language
VTK	Visualization Toolkit

Chapter 1

Introduction

1.1 Research background and problem statements

Developed countries are transforming a society based on mass production and consumption into one that uses the accumulated building stock to promote sustainability and prosperity. The extensive existing building stock plays a significant role with social, economic and environmental impacts. As a result, there is a burgeoning demand for renovation of the existing stock that goes beyond mere renewal or modification and instead aims at a complete reimagining of buildings in line with the current social climate (Shimabara & Hirano, 2014). This shift is not only about changing physical spaces, but also about promoting health and wellness within buildings, recognizing that people spend approximately 87% of their time indoors (Klepeis et al., 2001).

Renovation of the building stock is of great importance for modern societies, which focus on sustainable development and at the same time have a significant amount of existing structures (Fufa et al., 2021). The renovation and upgrading of existing buildings is a key strategy for improving energy efficiency, reducing greenhouse gas emissions, and ensuring the responsible use of resources (Jensen et al., 2022). It contributes to the preservation of historical and cultural heritage while adapting older

structures to meet current safety and comfort standards (Loli & Bertolin, 2018). Through thoughtful renovation, communities can revitalize urban areas, improve the quality of living spaces, and promote sustainability, ultimately contributing to the broader goals of sustainable development and environmental stewardship (Remeikienė et al., 2021). At the same time, it addresses the need for comfortable and healthy indoor environments by considering indoor environmental quality (IEQ) and its impact on occupant health and comfort, aspects that have traditionally been prioritized in new building designs. However, it's crucial to recognize that the existing building stock significantly outnumbers new construction and retains immense value from a social, economic, and environmental perspective (Kovacic et al., 2015). Therefore, the focus is on rejuvenating these existing structures, giving them a new lease of life through renovation, rather than opting for new construction.

As one of the main objectives of the renovation of existing buildings, the buildings should be designed to save energy, be environmentally friendly, and provide a comfortable living space (Tanabe et al., 2013). Poor indoor thermal experience accounts for a large proportion of homeowners' complaints (Zhu et al., 2016). As a result, home renovation has become a common choice to improve the indoor thermal environment, which typically includes window replacement, better insulation, installation of a more efficient heating system, and improvements to the home's airtightness and natural ventilation using mechanical ventilation systems (Hurnik et al., 2018). However, improvements in the indoor thermal environment are hampered by an outdated retrofit design process that fails to efficiently coordinate design aspects (architectural, equipment, structural, and environmental) while solving problems and addressing the feedback loop in a timely manner. Therefore, the integration of building performance feedback into the design process is increasingly being considered as a core element of the decision support framework that is currently driving sustainable buildings from early conception to fabrication (Chronis et al., 2017). The renovation process requires simultaneous architectural, system, structural, and environmental design to achieve a

healthy, comfortable, and energy-efficient indoor environment, avoid delays in problem solving, and achieve a timely feedback process. The renovation design process typically follows a waterfall model that is sequential and noniterative. Because all design steps are not synchronized and thermal design is an afterthought in the waterfall approach, feedback from the client comes too late (Laplante & Neill, 2014). If one of the design steps performed in the latter process encounters problems, there is no way to provide feedback on the design of the former process. This problem has led to unpleasant experiences for passengers. In recent years, several new methods have been proposed for a more efficient building design process that encourages stakeholders to collaborate in a synchronized manner (Hartog et al., 2000). Building Information Modeling (BIM), which includes current geometric information and building characteristics, is an emerging method for managing building lifecycles (Eastman, 2011), and it has been proposed to realize simultaneous building design considering the lifecycle data of the entire structure (Ghassemi & Becerik-Gerber, 2011). In addition, computational fluid dynamics (CFD), which uses numerical methods to solve fluid mechanics problems, can be used to analyze fluid flows in the design of thermal environments. Building design using CFD and BIM can streamline the design cycle and improve coordination among all building design disciplines. However, simply inputting CFD information into the BIM model does not allow all stakeholders to participate in the environmental design. One of the challenges for stakeholders is how to intuitively integrate BIM with CFD software. Methods have been proposed to integrate BIM and CFD, such as Autodesk CFD and DesignBuilder (Albatayneh et al., 2017; Boafu et al., 2015). CFD analysis produces a large amount of numerical data, which can be used in three-dimensional (3D) modeling with the proposed post-processing software. However, such software is not open source and cannot export the arrows and color map information of simulation results as vector data (Fukuda et al., 2015). The integration of CFD results with other systems has many limitations. In addition, it is difficult to establish a relationship between the CFD model and the BIM model in the 2D display. Suppose

the indoor environment can be displayed in an immersive manner to provide a more intuitive experience. In this case, communication between designers from different departments will lead to more accurate and faster implementation of a design to increase customer satisfaction.

Mixed Reality (MR) is a continuum between the real world and the virtual world that blends digital content with content from the physical world, allowing users to experience the interaction between the physical and digital worlds in real time (Milgram & Kishino, 1994). Diminished Reality (DR) is a specific technology that alters the user's perception of the real world by removing or hiding real objects from the user's visual environment (Cheng et al., 2022). Some studies have shown that the combination of MR technology and BIM in the building renovation process can reduce the cost and environmental impact during the renovation process (Chai et al., 2019; Prabhakaran et al., 2020). The introduction of MR technology in the renovation design steps enables the simultaneous design of the building plan and the environmental design, which can reduce construction time with less coordination, timely feedback, and fewer change orders. The MR experience also enables non-experts to understand and participate in the design process. MR spans the spectrum from real to virtual environments. Augmented reality (AR) adds virtual elements to the real world, and virtual reality (VR) immerses the user in a virtual space. DR, on the other hand, is a lesser-known term than AR and VR, and can be understood as the removal or modification of real-world content (Nakajima et al., 2017). The introduction of DR technology allows users to have an indirect view of the world, in which certain objects are made invisible, making it easier to present interior renovation plans, as the removal of an existing wall is one of the basic steps in the renovation of existing buildings.

There are many ways to achieve DR, but the most important aspect is the creation of the erased part. In this study, this aspect is referred to as the DR background, which aims to improve the overall experience with a more satisfying DR result. In-painting is

one of the methods that attempt to apply textures and patch details directly from the source image to paint over objects (Herling & Broll, 2012). New algorithms for image in-painting methods are constantly proposed, such as combining Visual-SLAM (Simultaneous Localization and Mapping) into the algorithm, which is a method that segments the background surfaces by using some feature points of the background (Kawai et al., 2013). However, these methods that combine visual SLAM are not available on solid colored or large area walls. In addition, the more satisfactory the DR results are, the more computational resources are needed (Sasanuma et al., 2016). Then, the computation time will increase, and real time DR will be difficult to realize. On the other hand, in-painting methods are usually used to erase small and independent objects, rather than for room-based interior renovation designs. This approach may have limitations when dealing with complex indoor environments. For example, building structures such as walls and columns are relatively large objects that are connected to the environment. Therefore, it is difficult to use the in-painting methods to erase large objects such as an entire wall. This research proposed a novel DR background generation method that can achieve realistic large-scale DR in real time.

Another set of methods uses pre-captured images or video of a background scene (Cosco et al., 2009). Later, when new physical elements are introduced into the space, the background images serve as a reference and provide information about the areas obscured by these new objects. Those methods that rely on pre-captured backgrounds cannot display the real time background and limit the viewing angle provided to the user to that of the pre-captured background. Therefore, to achieve realistic large-scale DR, it is necessary to virtually reconstruct a 3D DR background area.

Previously, a system using multiple handheld cameras for DR was introduced (Enomoto & Saito, 2007). In this system, multiple cameras were used to capture the same scenes from different angles. AR markers were used to calibrate these cameras, which allowed the calculation of occluded content and the reduction of target objects. However, the

DR results from this method were not consistently stable, primarily because its pixel-by-pixel comparison algorithm falters when the occluding object lacks color variations on its surface. Another advanced DR technique uses an RGB-D camera to occlude trackable objects (Meerits & Saito, 2015). In this approach, the RGB-D camera is used to assemble the missing segments, and then a color correction method is applied to unify images from different cameras. Due to inherent limitations in the performance of the RGB-D camera, the reconstructed images often contained gaps that resembled black noise. Although in-painting techniques were implemented to address these inconsistencies, the overall quality of the DR results remained suboptimal, with some residual black noise.

With the development of artificial intelligence, Generative Adversarial Networks (GANs) have been used to generate data via deep learning, proposing new image generation methods (Goodfellow et al., 2014). A stable GANs model was trained, demonstrating models for generating new examples of bedrooms (Radford et al., 2015). A study also shows that training synthetic images and optimizing the training material can help to better recover target images, facilitating many image processing tasks (Zhu et al., 2020). In addition, identifying different underlying variables can help to edit scenes in GANs models, including indoor scenes (Yang et al., 2021). However, there are not many GANs training models specifically for indoor panoramic images. Even when using indoor images synthesized from multiple angles, it's difficult to maintain a consistent style for objects in the same location. Using such synthesized images, it's virtually impossible to accurately reconstruct the indoor environment.

In summary, this study attempts to address the challenge of integrating CFD, MR, BIM, and GANs technologies in the field of retrofit design of existing buildings to meet the escalating demand for sustainable, comfortable, and energy-efficient living spaces. The fusion of these tools and techniques is expected to catalyze a design process that is not

only more efficient and collaborative but also more intuitive, ultimately facilitating simplified IEQ improvement.

1.2 Research objectives

This research has successfully developed a comprehensive MR system for building retrofits, integrating CFD analysis and MR technology to facilitate the simultaneous design of the building plan and thermal environment during the renovation process. Subsequently, the implementation of GANs allows occupants without professional skills to participate in the design process using hand-drawn sketches. At the same time, the integration of Wi-Fi facilitates the connection of multiple head-mounted displays (HMDs), supporting a synchronized experience for multiple participants. The system is divided into three main stages:

- 1) To develop an existing building renovation application using CFD analysis and MR technology to enable the simultaneous design of the building plan and thermal environment during the renovation process.
- 2) To introduce the DR method with GANs to enable occupants without professional skills to add or remove interior objects and modify structures by hand drawing.
- 3) To improve the system by supporting real time interactive communication between multiple people.

1.3 Research significance

The research is of significant importance in the field of building renovation and interior design, introducing an innovative integrated system that combines CFD and MR methods. This system significantly enhances the design and evaluation process of buildings and thermal environments, providing a more interactive and immersive experience for stakeholders. By visualizing CFD results and proposed design changes

in real time on HMDs, the research facilitates a deeper understanding of design concepts for all stakeholders, regardless of their technical expertise. This leads to improved communication efficiency between non-experts and experts, ensuring that design intentions are clearly communicated and understood. The use of GANs for DR functions and SLAM-based MR further extends the capabilities of the system by allowing virtual alteration of physical spaces (e.g., erasing a wall) to evaluate potential renovations. This enhances the decision-making process by providing a variety of design options and allowing stakeholders to interact with and understand these options in a more tangible way.

1.4 Research scope

The scope of this research is focused on the retrofit of existing buildings, with particular emphasis on the integration of the retrofit process and MR methods to optimize the design and evaluation of the building and thermal environment. The research addresses both the real indoor environment augmented with digitized CFD data and the simulated indoor environment augmented with real data. The developed system provides a platform for stakeholders to actively participate in the design process, offering the ability to modify the indoor layout, simulate different design proposals, and evaluate their impact in real time. The application of GANs for DR and SLAM-based MR technology is a key aspect of this research, facilitating intuitive evaluation of renovation plans and enhancing communication between different parties involved in the renovation process. The research focuses specifically on interior renovation, providing solutions to challenges such as virtually removing walls to connect rooms and ensuring stable and accurate visualizations of proposed changes.

1.5 Research framework

To implement an innovative MR system for building renovation design, the research framework of the system is divided into four steps (Figure 1.1):

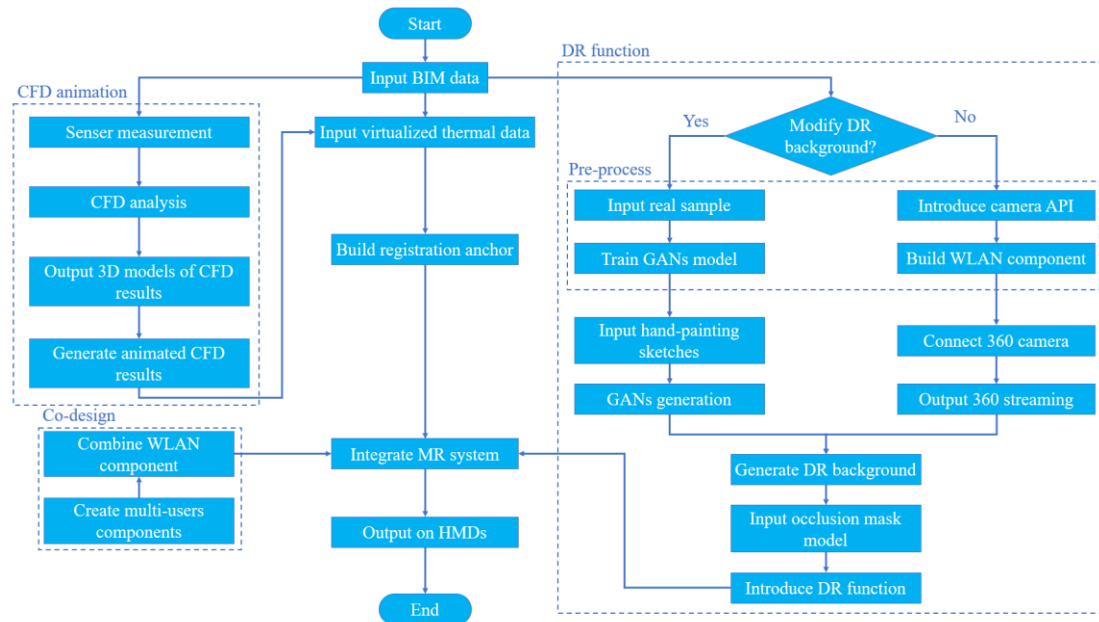


Figure 1.1 Research framework

1.6 Overview of dissertation

Figure 1.2 shows the overview of this research and the dissertation is organized as follows.

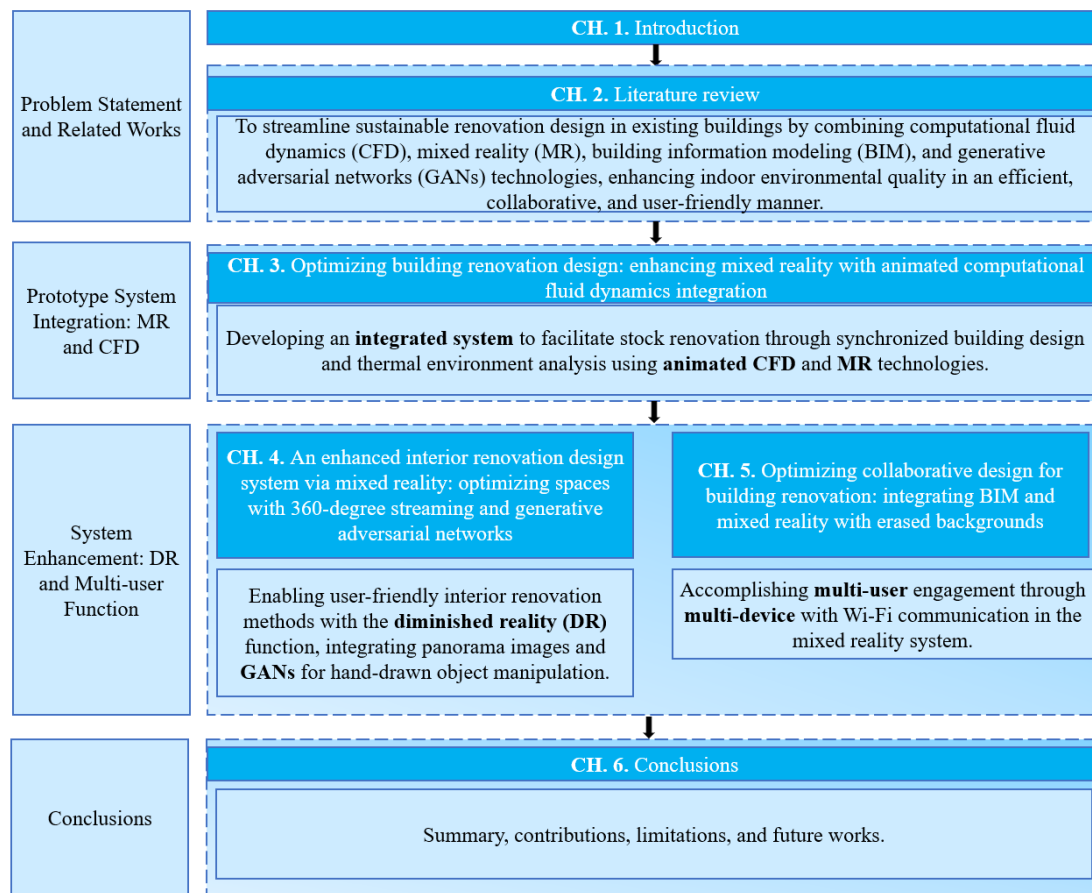


Figure 1.2 Overview of this research.

Chapter 1 Introduction

This chapter introduces the background information, problem statements, research objectives, research significance and scope, research framework, and outlines of this dissertation.

Chapter 2 Literature review

This chapter provides the related work of this study, including concepts, data, and methods of evaluating building renovation design in previous research. Specifically, it includes some applications of MR, VR, and DR technologies in architectural design, the method of using GANs to generate images from images, and the impact of improving indoor environment through building renovation on human health. It identifies the research gaps and opportunities for deep learning and MR approaches to

constitute a new research paradigm for creating, implementing, evaluating, and understanding building renovation design.

Chapter 3 Optimizing building renovation design: enhancing Mixed Reality with animated Computational Fluid Dynamics integration

In this chapter, an application is developed that integrates CFD analysis and MR technology for the rehabilitation of existing structures. The development process of this system includes four main steps: BIM modeling, mesh generation, CFD analysis, and MR visualization. In addition, a voice command system has been incorporated to facilitate easy switching between different observation scenes.

Chapter 4 An enhanced interior renovation design system via Mixed Reality: optimizing spaces with 360-degree streaming and Generative Adversarial Networks

This chapter implements an innovative DR function that can make a wall appear transparent, revealing the real time details of the scene behind it. A 360-degree camera is used to capture real time panoramic images, ensuring seamless integration of the virtual and real worlds. GANs are used as one of the methods to generate the DR backgrounds. This integration is achieved through accurate occlusion, which enhances the sense of realism within the MR environment.

Chapter 5 Optimizing multi-users design for building renovation: integrating BIM and Mixed Reality with erased backgrounds

In this chapter, the system is enhanced with real time interactive communication and a new method for DR background which support multi-users experience. Depth cameras capture the environment and translate it into point cloud data to support the manual creation of models. These meshes and 3D models are then used to construct a virtual target room tailored to the specific requirements of the DR background. To facilitate seamless interaction, all HMDs are connected via a wireless local area network (LAN) set up via a router, ensuring robust and efficient communication.

Chapter 6 Conclusions

This chapter presents the research conclusions, summarizes the key findings of the study, addresses the limitations, and outlines opportunities for future work.

Chapter 2

Literature review

This chapter presents the related work of this dissertation. It is organized as follows. Section 2.1 introduces the concept and category of MR, AR, and VR, as well as the definition of evaluation factors for indoor renovation. Section 2.2 reviews the multiple DR methods and deep learning methods. Section 2.3 provides a comprehensive review of various MR methods utilized to facilitate co-design processes.

2.1 Improving building renovation design through Mixed Reality and Computational Fluid Dynamics integration

CFD analysis facilitates the simulation of the indoor thermal environment, taking into account factors such as daylight and ventilation, making it an indispensable tool for evaluating indoor conditions (Bournet & Rojano, 2022; Bay et al., 2022). The data obtained from CFD calculations require a certain level of expertise for visualization purposes alone. Therefore, research in the area of CFD visualization technology has received increasing attention (Deininger et al., 2020). MR is an all-encompassing term that encompasses all immersive environments created by computer technology and wearable devices. In contrast, AR is a subset of MR that focuses primarily on simple overlays of virtual elements in the real world and is often used for practical applications such as mobile applications. MR also differs from VR, which is a completely virtual

environment where the real world is invisible. Therefore, MR can be considered as a collective term for these two technologies, with an emphasis on extending and enhancing the user experience (Alizadehsalehi et al., 2020). In recent years, the emergence of MR technology has introduced a new approach to CFD visualization. A lot of research has been done on the use of VR or AR technologies to display CFD results (Yan et al., 2020; Solmaz & Van Gerven, 2022).

2.1.1 Virtual Reality

VR is an artificial environment generated by computer graphics (CG) that can reproduce the human sensory experience to bring the virtual world closer to reality (Steuer et al., 1995). Compared with the conventional method of displaying CFD results in 2D using an LCD monitor, the various methods of visualizing data in 3D space are said to provide a better immersive experience. Therefore, VR technology has been proposed to bridge the communication gap between building designers and their clients. Unity game engine and video is one such interactive visualization system (Berger & Cristie, 2015), however, the timeline information of CFD simulation results is not available and the results are displayed on a 35 megapixel video wall (8k in 4×4 2k screens), which is not immersive enough. To provide the most effective VR experience, a cave automatic virtual environment (CAVE) has also been proposed (Ohno & Kageyama, 2007), but it is very expensive with a large number of low-versatility equipment. In one study, a CFD analysis was performed in a lecture hall and the results were displayed alongside the building model (Savioja et al., 2003). The airflow behavior and intensity are clearly shown by the visualized CFD results, but the created VR world has no connection to objects in the real world, making it feel different from the real world.

New methods with high versatility and high immersion using a HMD to view the thermal environment have been proposed in recent years. Fukuda et al. (2015) visualized a 3D design plan and CFD analysis results in VR space; however, the CFD

results could only be displayed as a heat map, and the changes in the heat map at different positions could not be viewed in real time. To solve these real time display problems, Hosokawa et al. (2016) proposed in another study to integrate CFD and VR using the Visualization Toolkit (VTK) library to make the indoor thermal environment easy to understand by allowing users to observe the entire 3D model of the CFD results.

2.1.2 Augmented and Mixed Reality

AR extends or enriches the real world by overlaying digital content on a real-world display. Research has been conducted on AR visualization by overlaying real-world models. One study presented real time visualization of temperature and volume data using a wireless sensor network (Goldsmith et al., 2008). But simply overlaying sensor data and real-world objects doesn't allow users to quickly understand thermal intelligence. An AR system was developed to display the indoor thermal environment of a room calculated by CFD based on data collected by room sensors (Malkawi & Srinivasan, 2005). The CFD results were exported to a Virtual Reality Modeling Language (VRML) file (Yabuki et al., 2012), and the AR method was used to associate point group data containing the CFD results with natural feature points. This allowed the VRML file to be visualized in large outdoor areas. Markerless AR was used to present the outdoor airflow calculated by CFD using data from global positioning system (GPS), gyro, and acceleration sensors (Heuveline et al., 2011). Another interactive visualization system using marker-based AR was proposed to improve the connection between CFD results and the real world (Fukuda et al., 2019). Although this system could display CFD results on a video see-through HMD, it could only display the thermal environment at discrete points in time; therefore, the result could not express the entire process of changing the thermal environment. This AR system superimposed the CFD information on the video as heat maps and arrows without occlusion, which means that the interaction with the user depended on the AR marker, and the relationship between the CFD results and the real world was very weak. In

addition, the user's activity area was restricted by the AR marker, which also resulted in poor user experience. The traditional interactive devices between the system and the human, such as the PC keyboard, mouse, or gamepad, require time to get used to (Fiorentino et al., 2014). In addition, when wearing the HMD, the line of sight is concentrated on the screen, and the user is laborious to see the interactive device. This brings a lot of trouble to the immersive experience. Therefore, the voice-controlled AR system has been proposed, which simplifies the operation steps, and users with no computer experience can quickly start using the AR system (Nishihara & Okamoto, 2015).

2.1.3 Indoor Environmental Factors

In the energy consumption of buildings, daylight is always a significant part of the energy consumption. It has an important influence on building energy consumption, where solar radiation increases indoor temperature and solar illuminance affects artificial light. Daylight is an essential external factor that must be considered to accurately predict the indoor environment (Buratti et al., 2017). Researchers typically analyze indoor daylight to predict indoor illuminance. An annual daylight simulation method has been proposed to predict daylight illuminance (Yoon et al., 2016). In addition, a new model was proposed to correctly simulate indoor illuminance (Fakra et al., 2011). In these studies, temperature was not the main consideration. The present study attempts to address this by considering daylight as one of the factors affecting the indoor thermal environment. One way to combat solar heat gain is to improve the energy performance of the building envelope. Windows are considered to be a weak point in the building envelope. Therefore, new window technologies, materials and structures have been proposed to control the influence of solar radiation on buildings to reduce energy consumption. For example, thermotropic windows can reversibly change the light transmission behavior (Yao & Zhu, 2012), and electrochromic glazing of windows can modulate the solar energy input by applying voltage (Paule et al., 2017).

Before adopting any of these solutions in building retrofits, simulations should be performed to determine their effectiveness using simulation software such as DeST (Yan et al., 2008), DIAL+ (Paule et al., 2012), ANSYS CFD (Panchal & Shah, 2013), etc.

Among the factors that influence the thermal environment of a building, air temperature is fundamental. Ventilation and thermal comfort are closely related. Poor ventilation can lead to high levels of carbon dioxide indoors, which can make people feel sleepy and have a negative impact on their health. Natural ventilation improves indoor air quality by promoting indoor-outdoor air exchange. The benefits of natural ventilation can be enjoyed even on cold winter nights. One study showed that opening windows just enough improved air quality and comfort during sleep, even though it slightly lowered the indoor temperature (Lei et al., 2017). In addition to the health benefits, natural ventilation is also energy efficient. For example, a low-cost natural ventilation solution can help cool buildings and improve indoor comfort in summer (Kubota et al., 2009).

2.2 Optimizing Mixed Reality interior renovation system with Diminished Reality and Generative Adversarial Networks

Interior renovation is the process of upgrading and modifying existing architectural structures and elements to make them more environmentally friendly, and safer, or to meet other new needs. In the early stages of traditional design processes, designers use blueprints to communicate with stakeholders. With sufficient budget and time, miniature physical models of the interior design, made of materials such as paper or foam, are occasionally created to facilitate more tangible communication with stakeholders. Whether hand-drawn blueprints or hand-crafted physical models, they are typically more time-consuming than digital methods, and human error can introduce

inaccuracies in measurement or design. In addition, with hand-drawn designs, any changes can require significant time and budget, and may even require the entire design to be redrawn a common cause of time overruns in architectural projects (Chan & Kumaraswamy, 1997). In the early stages of the design process, the use of digital methods allows for more convenient sharing with team members or clients. Feedback is accelerated and the cost of changes is reduced (Watson, 2011).

2.2.1 Interior renovation with VR

Compared to demolition and reconstruction, interior renovation is proving to be a more environmentally friendly, budget-conscious, and efficient method of giving existing buildings a new lease on life. A digitized interior model is essential to ensure that clients without specialized knowledge receive renovation results that meet their expectations. Unlike the more technically demanding blueprints, 3D models allow clients to immediately grasp the expected results of the renovation, provide feedback, and get involved in the design process.

Compared to traditional methods that use desktop displays to present renovation results in a 2D plane, VR technology, which visualizes various data and interior models in 3D space and allows clients to immerse themselves in the renovation results from a free-viewing experience, has been proposed to bridge the communication gap between designers and their clients (Ozdemir, 2021). Furthermore, the reliability and applicability of using VR technology within the architectural design process have been validated (Woksepp & Olofsson, 2008). Compared to traditional tools, immersive VR technology has significant advantages within the interior architectural design process (Lee et al., 2023). However, although VR technology in interior design has matured significantly, it also presents some problems. VR creates an entirely virtual environment, requiring the computer to generate a comprehensive 3D model of the building's interior. In order to provide a more realistic immersive experience, some places that do not require renovation must also be modeled. For example, even if only part of a room is

being renovated, the entire room must be modeled for a more authentic experience, including objects that serve only as a backdrop. The high up-front costs may cause designers to lose some clients who have not yet signed a contract. In addition, the more realistic the VR experience, the larger and more expensive the equipment required, further increasing the cost of modeling. Examples of such equipment include gigantic high-resolution displays composed of multiple screens (Chandler et al., 2015) or the CAVE system, in which an entire room is transformed into a display (Ohno & Kageyama, 2007).

2.2.2 Generate virtual environment using Generative Adversarial Networks

With the advancement of artificial intelligence, deep learning has introduced a variety of new and efficient approaches to image and model generation, among which GANs stand out. 3D model creation is a complex and costly process that involves 3D acquisition, 3D reconstruction, and rendering using computer graphics technology. By using GANs, a large number of house models can be automatically generated based on some simple requirements and prompts provided by the user, such as keywords, sketches, or color blocks (Liu et al., 2021). In addition, the use of different training datasets can result in different image effects that exude a unique style. For the renovation of old houses that lack BIM data, the house point cloud data obtained by a laser scanner or depth camera, or photographic data captured by cameras, can be input into the GANs method, which can be used to quickly perform automatic 3D model reconstruction (Yun et al., 2018). These procedures proved to be highly beneficial for the early process of interior renovation design using MR technology, which improved the feedback speed throughout the process while reducing the cost of model construction. In addition, the method of using a 360-degree panoramic camera to capture the target space using panoramic photos or videos as the MR environment has also been proposed (Teo et al., 2019). In an indoor environment where the structure is not overly complex, the capture range of a 360 camera can almost cover most of the

area observable by the human eye. Compared to the generation of an indoor environment using camera scans or multiview photos, panoramic photos can complete the collection of environmental data in an instant and have a dominant advantage in generation speed. Although panoramic photos have some shortcomings in terms of image quality, several solutions using GANs technology have been proposed to address this issue (LI et al., 2022; Lin et al., 2019).

2.3 A Co-Designing system with building information modeling, Mixed Reality, and background removal

New design tools are fundamentally changing the way designers create physical products, resulting in a seamless, human-centered experience (Novak and Loy, 2018). In addition, communicating with occupants helps designers implement their ideas and make a design more appropriate for them (Jonson, 2005). Communication with occupants has always been an important issue for designers. Studies have shown that establishing a remote collaboration system using MR technologies to provide visual cues to occupants improves their communication experience and increases their level of engagement (Gauglitz et al., 2014; Wang et al., 2023).

2.3.1 Virtual Reality based co-design method

The role of computer-aided architectural design is seen as the basis for the development and further improvement of the architectural design process. VR, an artificial virtual environment generated by CG, can replicate the human sensory experience in a virtual world (Slater et al., 2016). This shows great potential for supporting architectural design, and is often used in the early stages of environmental design. Initially, user interfaces were created and people could observe the design in a VR environment from a computer monitor (Daniel and Irizarry, 2018). Next, with the advent of HMDs, an immersive interactive 3D virtual environment was developed to provide residents with a much

better understanding of urban environmental parameters that can be experienced by a limited number of people simultaneously (Bondakji et al., 2019). In addition, a VR-based co-design method has been proposed to allow simultaneous participation of multiple users in workshops (Dembski et al., 2019). However, the problems are the high cost and low portability of the equipment.

2.3.2 Mixed Reality based co-design method

Compared to VR, where you are immersed in a virtual world, MR is a technology that blends digital content with physical content, allowing users to experience the interaction between physical and virtual worlds in real time (Milgram and Kishino, 1994). In addition, DR has the function of visually reducing existing physical objects and can provide an intuitive and easy-to-understand solution for displaying design plans. This can improve the communication efficiency of design participants during the design process. A method using MR with a DR function to display indoor renovation plans has been proposed (Zhu et al., 2019). However, multiple users cannot interact in the same MR environment at the same time. A collaborative design system that allows multiple people to participate is needed. In addition, the communication between design participants cannot be directly reflected in an MR environment, which greatly affects the feedback efficiency during the design process.

2.4 Summary

In summary, creating an MR system for architectural renovation design is a challenging task that requires the integration of multiple technologies. This multifaceted approach ensures a comprehensive solution that addresses different aspects of the design and renovation process. The following sections are intended to provide a summary of the research gaps and objectives, outlining the areas that need further exploration and the goals that the study aims to achieve.

Currently, the methods for presenting CFD results are predominantly numerical, iconographic, 2D animations and models. This study takes a significant leap forward by using 3D model animations to present CFD results, allowing for comprehensive viewing of the results in an MR environment, rather than being limited to 2D monitors. This advancement improves the interpretability and accessibility of CFD results, providing a more immersive and intuitive understanding of the data.

The incorporation of VR creates a fully virtual environment, where architectural layouts must be computer generated, and more realistic models come at a higher cost. In addition, VR environments are rarely designed to interact with the real world, which limits their use in architectural design. This limitation creates challenges for designers and stakeholders who want to visualize and interact with design elements in the context of the existing physical space.

MR enriches the real world by overlaying digital content on top of the representation of the real environment, reducing the cost of modeling compared to VR. However, simply overlaying sensor data and real-world objects is not enough for users to quickly understand the thermal environment. Current MR systems face challenges in correlating CFD results with the real world, such as displaying only discrete points of the thermal environment over time and failing to convey the entire process of thermal environment changes. In addition, superimposed heat maps and arrows in MR lack occlusion, and user interaction relies heavily on MR markers, resulting in a weak connection to the real world. User activity areas are also limited due to the reliance on MR markers, negatively impacting the user experience. In contrast, this study uses an MR system that provides a comprehensive view of the entire thermal environmental change process, detects correct occlusions using a depth camera, and uses simultaneous localization and mapping technology for registration without the need for physical markers, thus providing an unrestricted activity area.

Traditional human-computer interaction devices, such as PC keyboards, mice, or game controllers, require a period of adaptation. In this study, with the use of an HMD, the position of the device aligns with the user's position, allowing the user to immediately dive into the MR experience without any additional manipulation. However, when using an HMD, the user's focus remains on the screen, making it difficult to see interactive devices, which can hinder the immersive experience. This chapter addresses this challenge by implementing voice commands to make interactions more convenient.

Current DR methods struggle to effectively remove existing structures or large furniture from indoor environments, often resulting in unrealistic results. This chapter used generated panoramic images as DR results and successfully removed large indoor areas. However, as in previous studies, there are noticeable problems with delay and latency in real time streaming. In addition, the efficiency and accuracy of occlusion generation (the process of correctly rendering parts of objects that are obscured by other objects) still need improvement.

Engaging non-experts in home design has always been a challenge. Previous studies have introduced several MR systems that allow simultaneous observation with professional designers, but non-professional participants rarely interact, with professionals primarily leading the demonstrations. This study proposes a novel approach using GANs to transform hand-drawn sketches into rendered images, significantly increasing the participation and involvement of non-professional stakeholders in the design process.

Chapter 3

Optimizing building renovation design: enhancing Mixed Reality with animated Computational Fluid Dynamics integration

3.1 Overview

Poor thermal experiences are a significant source of occupant dissatisfaction, as evidenced by numerous complaints (Rohdin et al., 2014). This has led many to opt for home renovations as a means of improving the indoor thermal environment (Hurnik et al., 2018). However, the traditional renovation design process, which often uses outdated methods and lacks efficient coordination between different design aspects (such as architectural, equipment, structural, and environmental considerations), tends to hinder improvements in the indoor thermal environment. It also struggles to address problems in a timely manner and to manage feedback loops (Häkkinen et al., 2012).

In contrast, emerging methodologies advocate for a more synchronized and collaborative approach to building design. BIM, a method that consolidates up-to-date geometric and property data of a building, has been identified as a powerful tool for

managing building lifecycles and ensuring comprehensive consideration of a structure's lifecycle data (Cheng & Ma, 2013; Feng et al., 2020). In addition, CFD, a technique that uses numerical methods to analyze fluid flows (Chung, T. J. 2002), is invaluable for the design of thermal environments. The integration of CFD and BIM has the potential to streamline the design cycle and improve coordination between different design domains (Lee et al., 2021). However, this integration alone does not guarantee stakeholder participation in environmental design. Visualization of CFD numerical results within BIM models provides stakeholders with an efficient and intuitive way to communicate design intentions and results (Fukuda et al., 2019). This integration enables a seamless transition of data from performance simulations to the visual domain, aiding in the interpretation and decision-making process for building design and renovation. A significant challenge is establishing an intuitive connection between BIM and CFD software. While integration methods such as Autodesk CFD and DesignBuilder exist, they are proprietary and do not support the export of simulation results as vector data, which limits their applicability (Giełżecki & Jakubowski, 2018; Daemei et al., 2016). Furthermore, it is challenging to display the relationship between CFD and BIM models in a 2D environment.

MR is a technology that merges the physical world with the digital world, which is often viewed as a spectrum that includes everything between the completely real and the completely virtual (Speicher et al., 2019). MR provides an immersive experience, and displaying BIM models in an MR environment can significantly streamline the workflow for on-site assessments in building renovation design projects. Similar studies have integrated BIM with MR technology, demonstrating that this combination accelerates the decision-making process and improves the overall quality of the project (Carbonari et al., 2022). This integration allows stakeholders to visualize and interact with the architectural design in a more immersive and contextual manner, directly at the renovation site. As a result, potential problems can be identified and addressed more quickly, leading to more informed and efficient design decisions.

This chapter proposes the integration of CFD and MR to merge CFD results with the real world, providing a more immersive and intuitive experience. This will improve communication between designers from different departments, leading to more accurate and efficient implementation of designs, ultimately increasing customer satisfaction. The system developed in this chapter focuses specifically on the renovation of existing buildings, integrating CFD and MR to facilitate the simultaneous design of the building plan and thermal environment, enriched with digitized CFD data presented in a 4D context.

3.2 Methodology

The MR system was proposed to bring together stakeholders, such as owners and designers, and involve them in the decision making process from the early stages of building design, allowing simultaneous design of the building and the thermal environment. The construction of the system involved the following four steps: BIM modeling, mesh generation, CFD analysis, and MR visualization, as shown in Figure 3.1. First, the BIM model of the target space was created according to the design drawings using the BIM software. All the information about the geometry, material, component properties, etc. were entered in this step. Second, the mesh used in the CFD calculation was generated based on the BIM geometry information. Third, the boundary conditions were set based on the BIM properties and the initial conditions were entered. Both of these operations were performed manually. Then, the steady-state fluid simulation was performed by the CFD software. Fourth, the CFD simulation results were exported and these data were converted to another format to generate the CFD animation. The animated CFD results were visualized in full scale and small scale by the Simultaneous Localization and Mapping (SLAM)-based MR technology. Finally, the voice command system was built to switch the observation scene. Users can easily understand the indoor thermal environment by switching scenes between different room scales, plans, heat maps, comfort maps, and streamlines animation.

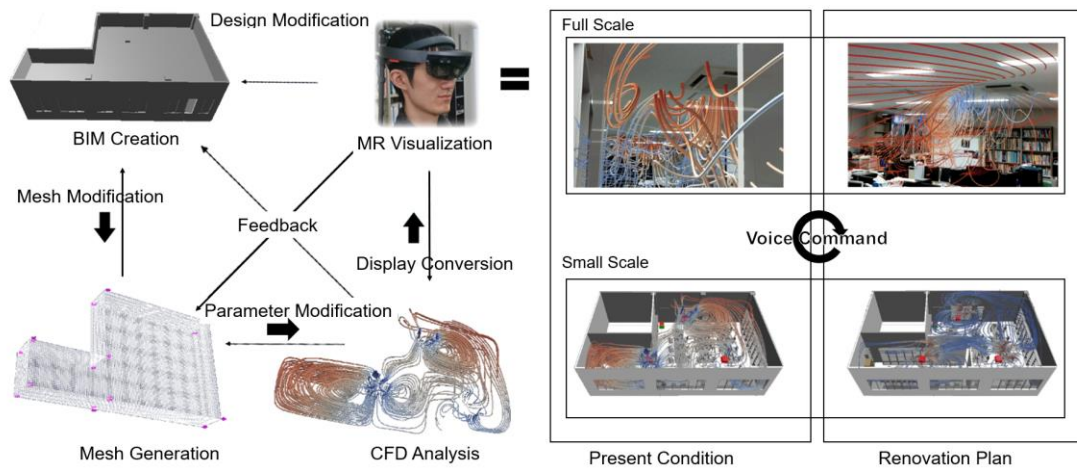


Figure 3.1 Overview of this chapter.

3.2.1 BIM modeling and mesh generation

The BIM model is manually created by BIM software. As an evaluation system, the BIM model can manage the lifecycle of the entire project, allowing users to obtain information immediately. It also provides the volume mesh needed for CFD analysis. There are several methods for generating the mesh. Some methods require building the mesh from scratch; others, such as mesh generation software and 3D modeling software, can convert a 3D model into a mesh. Regardless of the method, BIM information is required and the output mesh must be manually corrected before it can be imported into CFD software. In addition, the more complex the BIM model, the more time it will take. Mesh generation software should be used to generate the mesh in this chapter. The mesh data has been packaged in Polymesh for import into CFD software.

3.2.2 CFD analysis

For the CFD analysis, the boundary properties related to the wall, ceiling, floor, window, table, and heat source were manually set based on the BIM information. Initial conditions, including indoor temperature and air flow conditions, were set for the different case studies. A daylight factor was introduced, and its intensity was

determined by the sun direction and insolation set by the Japan Meteorological Agency database (JMA, 2023). In this study, the thermal environment of the building was assumed to be in a stable state. After the system settings such as parallel setting and time control were completed, the CFD analysis was performed using open-source CFD software.

3.2.3 MR visualization

Typically, people without professional knowledge cannot judge the indoor environment conditions just by looking at numerical results. However, the approach used in this method is to visualize the CFD results. By using different colors to depict temperature variations and adjusting the line thickness to illustrate flow rates, it separates the comfortable thermal zones from the unfavorable ones. This visualization technique is intended to bridge the gap between professional concepts and the understanding of non-experts. Numerical data of the indoor thermal environment were calculated after the CFD analysis. The data were imported into post-processing software and converted into 3D graphical information by adding different filters. The data was then exported frame by frame in VRML format. Next, the VRML files were converted into various formats that could be imported into the game engine platform, which is widely used for the development of integration systems. However, because the imported data files were converted from point cloud data, most game engines could not correctly read the complete data information. In particular, the geometric data are related, so after the data files are imported into the scene, the CFD model can be rendered. However, the temperature information was stored in the vertices as numerical data only. To display the temperature in the game engine platform, the temperature data was associated with RGB values by programming a shader script to detect the vertex color. With the addition of this script, the complete CFD results, including geometry and color data, could be displayed in the Unity game engine. In addition, the diameter of the streamlines was linked to the velocity of the airflow.

The conventional way to create the CFD animation is to convert the same angle of the 3D model at different times into frame animation (Ludwig et al., 2015). However, the same angle CFD animation would have many limitations, which might increase the difficulty of communication among stakeholders. To achieve a free observation angle, rendering each angle change in real time requires significant system resources. Therefore, another solution is proposed. The imported data files were organized in a sequence, and at each time step, the next frame model was imported and the previous frame model was destroyed. A JavaScript-based component was programmed to control this process. This allowed users to view the animated CFD data from all directions.

The CFD animation and MR system were run on different hardware, personal computers (PCs), and HMD. The HMD toolkit is a plug-in used to customize the MR system, pack the game engine content onto the HMD, and integrate the animated CFD post-processing data with the MR system. To ensure the correct display position of the simulated airflow model, the coordinates of the virtual world and the real world must be unified. A cube was created to locate the CFD result and the target space was also set as a world anchor, called the "anchor cube," to be able to adjust and ensure stable registration. It was bound to the SLAM-generated mesh to avoid manual re-registration each time the application was started. Over time, the results of the airflow simulation gradually became complicated, and users would lose the big picture of the entire indoor environment. To solve this problem, a scale change function was added to the MR system, allowing users to switch between full-scale and small-scale. In the full-scale mode, users could experience and observe the surrounding airflow; in the small-scale mode, users could see the entire room and therefore have a better overall understanding of the indoor thermal environment. In addition to the scale switch, the thermal images and comfort maps commonly used in thermal evaluation are added to the switch list, making it easy for non-professionals to participate in the design process. The comfort zone is where the indoor temperature is 27.2°C in summer and 17°C in winter, while

the upper and lower temperature difference is within 3 degrees (Matsuo et al., 2006; Jin et al., 2012).

Currently, many HMDs use gestures instead of mouse and keyboard to control the MR system. However, gestures often fail to perform some complicated operations, and users feel tired after using gestures for a long time (Nishihara & Okamoto, 2015). Compared with gestures, voice commands allow hands-free operation and can easily perform a series of complicated operations (Werrlich et al., 2018). Therefore, voice commands were added to allow users to switch between different room scales, plans, heat maps, and comfort maps, and to streamline animations to compare alternative designs.

3.3 Experiments and results

In order to test the proposed MR system with animated CFD in Chapter 3, the prototype system was developed in this chapter. An evaluation test was conducted in Room 411, Building M3, Suita Campus, Osaka University (north latitude: 34.82°; east longitude: 135.521°). Building M3 was completed in January 2015 and serves as a research building for the Graduate School of Engineering. It has a mix of research offices, lecture halls, and laboratories, and room 411 is a student office. The total area of room 411 is 150 m². There were three working air conditioners and 18 windows without curtains; the anchor cube was placed next to the front door (the same position in the real and digital world), where registration was provided (Figure 3.2). The start date and time of the analysis were set to 9:15 a.m. on December 17 and 18 in winter (GMT + 9). The solar elevation was 20.65° and the solar azimuth angle was 141.08° (due north, east, south, and west; azimuth is 0°, 90°, 180°, and 270°, respectively). As a control group, the shading panels were used to block daylight on December 17. In the CFD analysis, the position of the sun was determined using the above information. The solar irradiance was 90.28 W/m² according to the database of the Japan Meteorological Agency.

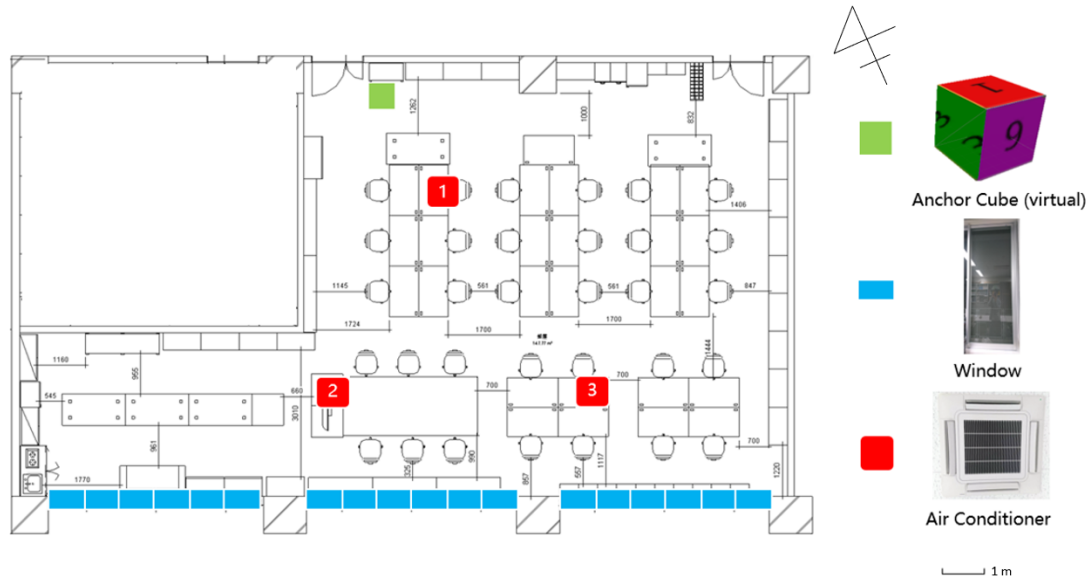


Figure 3.2 Room floor plan.

3.3.1 System data flow

The system flow is shown in Figure 3.3. First, the BIM model is created using Autodesk Revit Architecture 2016. The finished full-scale model is exported in STL format. Typically, the mesh used in the CFD simulation is generated using the BlockMesh method or SnappyHexMesh software. The BlockMesh method generates a hexahedral mesh by inputting a list of vertices and a rectangular parallelepiped. SnappyHexMesh software generates a hexahedral-based unstructured lattice by reforming the mesh created by BlockMesh according to the shape model as in the input STL files (Nozaki, 2018). Pointwise is a mesh generation software that is widely used in various research fields. It contains more supported interfaces than the normal methods, covering the whole preprocessing from the import of the geometry model to the export of the flow solver (Pointwise, 2023). The STL files are imported into the Pointwise software, which serves as a bridge between the model in Revit and the mesh in OpenFOAM (v1706). OpenFOAM is an open source software used to simulate fluid mechanics phenomena (OpenFOAM, 2023). Imported STL files are used to generate the mesh, which has to be manually modified as this generates a number of geometry errors. After error

correction, the mesh is exported as geometry files to the solver folder in OpenFOAM. During the CFD analysis with OpenFOAM, the user chooses a specific solver to solve a class of problems. Different solvers have different physical property settings (e.g. viscosity coefficient, thermal expansion coefficient, reference temperature). Collectively, the physical properties determine the thermal diffusivity (α), which measures the rate of heat transfer of the material from the hot side to the cold side (Den et al., 2000). The thermal diffusivity (α) is equal to ν divided by Pr , where ν is the viscous diffusion rate and Pr is the Prandtl number. Gravity is usually set to 9.8 N/kg. While a turbulence model has a stable state and an unstable state, for this study the situations were set to a stable state with multiple models built for each situation. Since there were not many complex conditions in the simulated target for this study, the standard κ - ϵ model was chosen. The calculations used the finite volume method to discretize the partial differential equations. The buoyantBoussinesqPimpleFoam solver was selected; the SolarLoad model was used to analyze the daylight factor; and boundary conditions, including mesh properties, air pressure, temperature, and flow rate from the power source, were set based on the BIM information. The results of the CFD analysis were output in VTK format. After the VTK files were imported into ParaView, the point cloud data was transformed into a model containing temperature and airflow distribution data. The VRML files were then converted to FBX files using 3ds Max software. To output the results of the dynamic indoor thermal environment to the HMD, the model files were first imported into the Unity game engine and the animation sequence was generated. Finally, the project was packaged into an application and installed on the HMD.

The MR visualization was implemented using HoloLens Gen 1, an optical see-through HMD that projects virtual objects directly onto a translucent screen to allow users to see the real world scene directly. It uses four environment understanding cameras with simultaneous localization and mapping algorithms to implement registration.

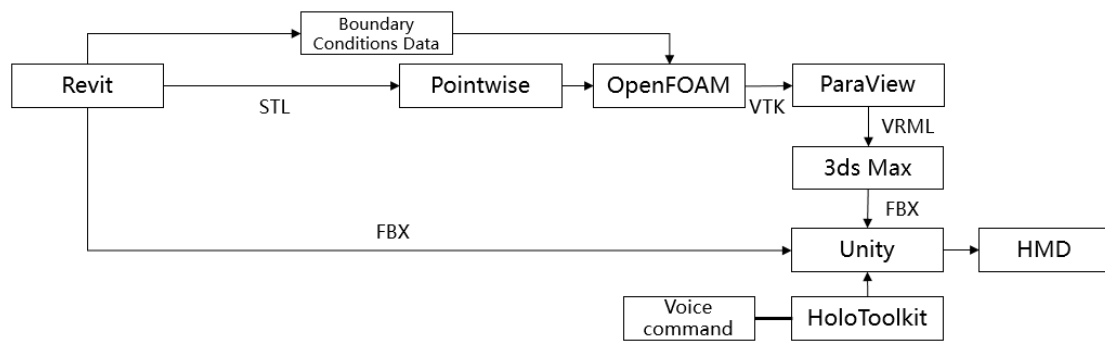


Figure 3.3 System data flow

3.3.2 Analysis conditions

The BIM model, as shown in Figure 3.4, for mesh generation or CFD analysis was created in Revit. The mesh and boundary setting were set based on the BIM model as shown in Figure 3.5 above. To improve the simulation accuracy, simplified tables were added to the mesh as shown in Figure 3.5 bottom.

The specific boundary conditions, including boundary radiation and material properties, are listed in Table 3.1. Temperature data were collected from sensors during the experiment. For each air conditioner, there were four outlets and one inlet, as shown in Table 3.2.

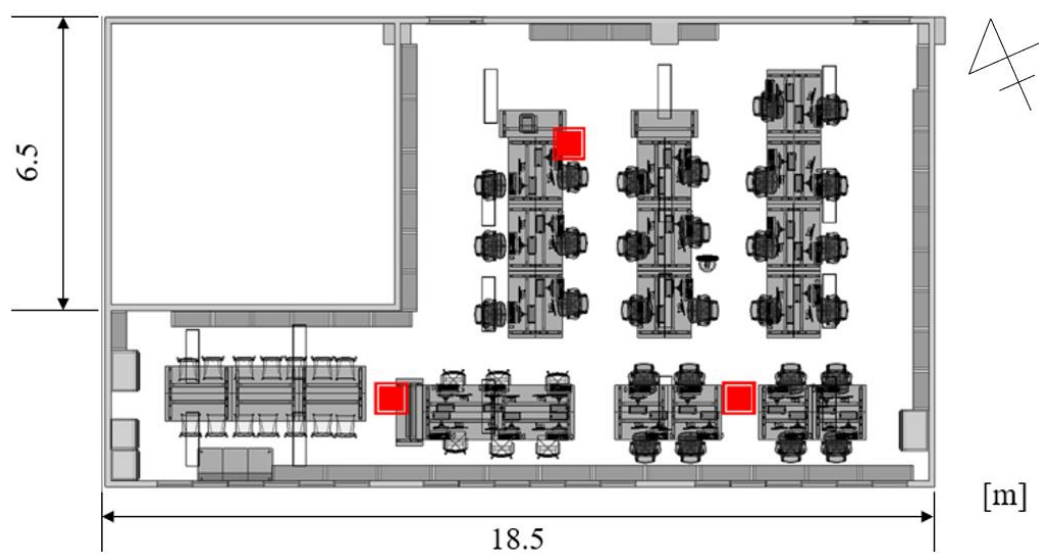
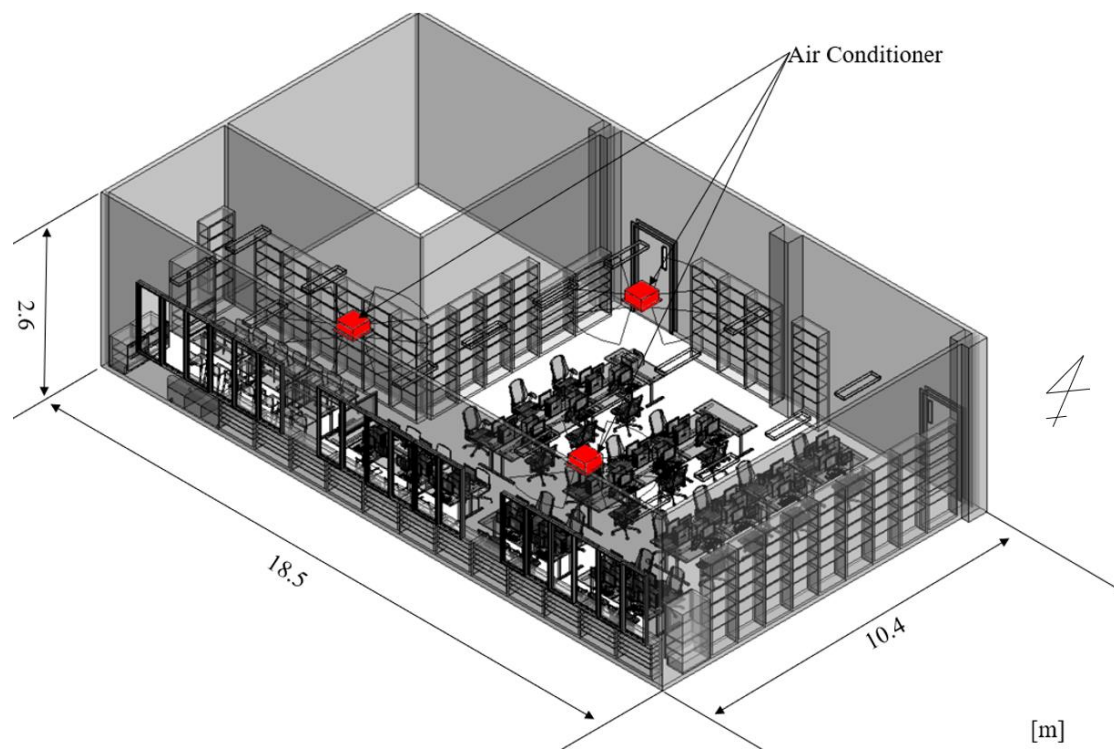


Figure 3.4 Room 411 BIM model

Table 3.1. Boundary conditions of construction materials

ITEM	WALL	CEILING	FLOOR	WINDOW
THERMAL TRANSMITTANCE [W/(M²·K)]	1.38	1.80	1.70	5.60
INITIAL WALL TEMPERATURE [°C]	19.6	19.6	19.6	14.7
OUTDOOR TEMPERATURE [°C]	14.7	14.7	14.7	14.7
EMISSIVITY	0.010	0.010	0.010	0.113
ABSORPTIVITY	0.700	0.700	0.700	0.815
TRANSMISSIVITY	0	0	0	0.815

Table 3.2. Boundary conditions of the air conditioner

ITEM	OUTLET	INLET
AIR VOLUME [M³/MIN]	18	18
AREA[M²]	0.06×4	0.36
SPEED [M/S]	2.5	1.2
TEMPERATURE [°C]	24	-
DIRECTION [°]	60	-

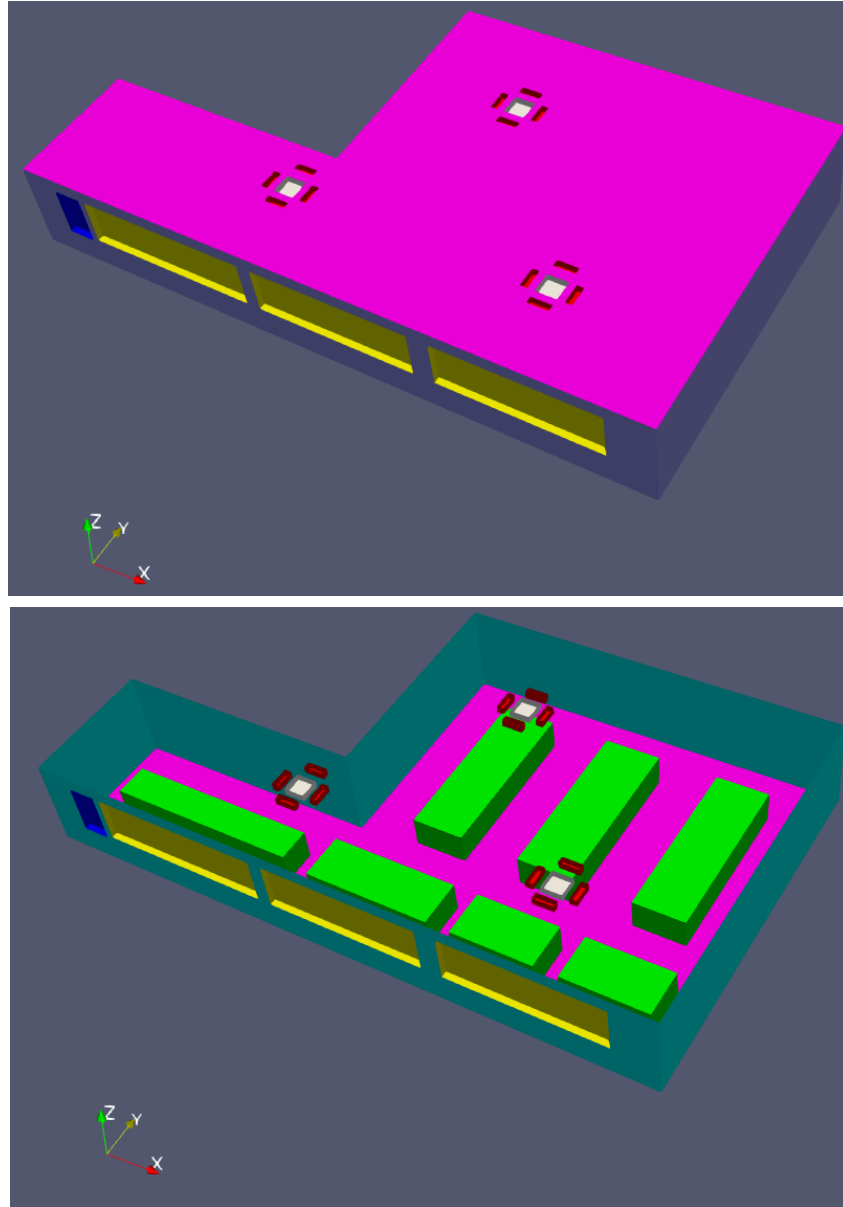


Figure 3.5 Room 411 boundary setting (Above / Bottom : with / without ceiling)

3.3.3 Operating environment

A prototype application was developed to verify the feasibility of the proposal. The prototype was developed according to the methodology proposed in Section 3.1. The BIM modeling, mesh generation and MR visualization were implemented using a desktop PC (A) (specifications in Table 3.3). The CFD analysis was performed using OpenFOAM software, developed in C++ language and running on Linux system. Therefore, two solutions were available: a virtual machine running the OpenFOAM

software and the Windows/Linux twin system. The first solution was limited by the CPU performance, as the CFD analysis required a lot of computing resources. Weak CPU performance slowed down the computational speed, delaying feedback on changes to the retrofit design. The dual Windows/Linux system was very unstable and systematic errors were common. Therefore, the prototype was split between two PCs and the CFD analysis was performed on PC (B) (specifications in Table 3.4).

Table 3.3. Desktop PC (A) specifications

ITEM	PERFORMANCE
OS	Windows 10 Enterprise 64-bit
CPU	Intel Core i5 7500 @ 3.40GHz
RAM	16.0GB Dual-Channel DDR4 @ 2400MHz
GPU	NVIDIA GeForce GTX 1060 6G

Table 3.4. Desktop PC (B) specifications

ITEM	PERFORMANCE
OS	Ubuntu 16.04
CPU	Intel Core i7 7700K @ 4.2GHz
RAM	16.0GB Dual-Channel DDR4 @ 2400MHz
GPU	None

3.3.4 Validation of simulation accuracy

Different from most studies in the literature review, this study used OpenFOAM, an open source CFD simulation software, with its daylight and natural ventilation considered. Therefore, it is necessary to test the accuracy of the simulation for this new combination, a measurement experiment was conducted that compared the temperature data from the sensors with the CFD simulation results following the same initial conditions.

- 1) Sensor installation: Ten sensors (Thermoclon G type, KN Laboratories) (Thermoclon, 2023), as shown in Figure 3.6 and Table 3.5, were evenly distributed throughout the room.
- 2) Comparison between experimental values and CFD simulation values: The analysis target time was set to 9:15 on December 17 without daylight (with shading panels) and on December 18 with winter daylight. The air conditioner ran for 2 minutes to obtain dynamic data. The winter measurement results are shown in Table 3.6 and compared with the simulated temperature values in Table 3.7. Each simulation contained over 370,000 data points. The maximum and minimum temperature values were removed to eliminate systematic errors. For the remaining data, decimal points were removed to obtain an approximate value. According to the results, the average temperature difference in the experimental results was 2.8°C, and the average temperature difference for the simulation was 2.91°C, an acceptable error difference of 0.11°C. The system error without daylight is 0.55°C, and the system error with daylight is 0.66°C. In addition, the experimental results confirmed the accuracy of the proposed simulation.

Table 3.5. Sensor specifications

	COMMON STANDARD SENSOR	HIGH-PRECISION SENSOR
RADIUS AND THICKNESS (MM)	17 x 6	17 x 6
WEIGHT (G)	3.3	3.3
MEASUREMENT RANGE	Temperature: -40°C to + 80°C	Temperature: -20°C to + 70°C Humidity: 0% RH to 95% RH
NORMAL RESOLUTION	Temperature: ±0.5°C	Temperature: ±0.5°C Humidity: ±6% RH
HIGH RESOLUTION	None	Temperature: ±0.1°C Humidity: ±0.1% RH
MIN MEASUREMENT INTERVAL	1 minute	1 second

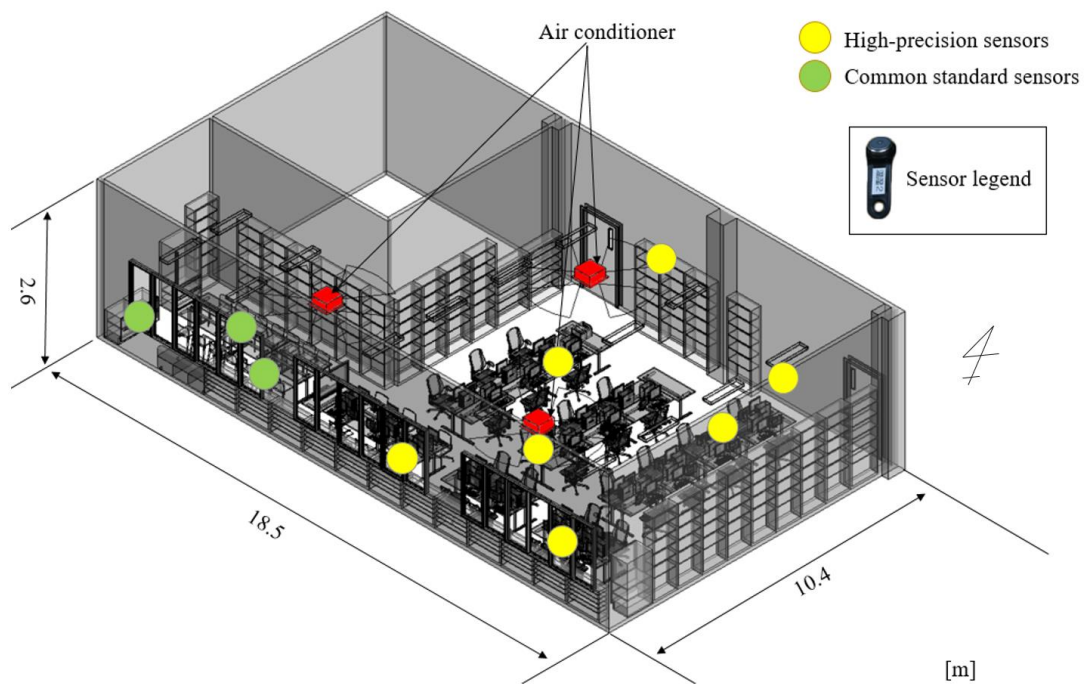


Figure 3.6. Sensor setting position

Table 3.6. Sensor measurement results in winter

ITEM	0 (MINUTES)	2 (MINUTES)
AVERAGE INDOOR TEMPERATURE (WITHOUT DAYLIGHT) [°C]	14.0	16.6
OUTDOOR TEMPERATURE (WITHOUT DAYLIGHT) [°C]	14.0	14.0
AVERAGE INDOOR TEMPERATURE (WITH DAYLIGHT) [°C]	14.7	20.1
OUTDOOR TEMPERATURE (WITH DAYLIGHT) [°C]	14.4	14.4

Table 3.7. Winter simulation results

ITEM	0 (MINUTES)	2 (MINUTES)
AVERAGE INDOOR TEMPERATURE (WITHOUT DAYLIGHT) [°C]	14.0	17.15
OUTDOOR TEMPERATURE (WITHOUT DAYLIGHT) [°C]	14.0	14.0
AVERAGE INDOOR TEMPERATURE (WITH DAYLIGHT) [°C]	14.0	20.06
OUTDOOR TEMPERATURE (WITH DAYLIGHT) [°C]	14.0	14.0

3.3.5 Simulation of renovation proposal

To operate the prototype system, it is assumed that room 411 requires renovation, and the room is distinguish the functions of different regions. The three types of differentiation are:

- 1) Divide the room into a kitchen area and a study area.
- 2) Divide the room into a bright area full of sunlight and a dark area without sunlight.
- 3) Divide the room into a hands-on experimentation area and a quiet study area.

The first type of partition separates the two functional areas and reduces the impact on students in the study area when cooking in the kitchen. In addition to potential noise, the smell and heat of cooking are also isolated. The second type of partitioning is based on the distribution of natural light. This allows students who like to bask in the sun and students who do not like to bask in the sun to freely choose their learning environment. The third partitioning method divides the functional area into an experimental area for discussion and a quiet study area. At the same time, the distribution of air conditioners and the proportion of room area are taken into consideration so that the temperature difference in the entire room is not too large.

The following specific settings were assumed in the evaluation experiments:

Case a: Divide kitchen and students' study space to reduce the effect between both parties.

Case b: Divide the room into two parts: one provided with natural light and ventilation and the other enclosed in an air-conditioned environment in order to meet the different needs of students.

Case c: Divide according to the ratio of air conditioning and room area for uneven temperature distribution of the air-conditioned room.

Three new building meshes were generated as shown in Figure 3.7. The same boundary conditions were applied as in Tables 1 and 2. The air conditioner was run for 2 minutes as in the validation. Each case was divided into three solutions: the original single-glazed window design and the new proposed double-glazed window design combined with the original metal sash material and the resin sash material. The thermal transmittance properties of the windows were calculated according to the method of Hosokawa et al. (2016). The values are given in Table 3.8. Daylight affects the indoor temperature, while the sash of different materials and the window of different structures would affect its result. Therefore, an experimental group without daylight is necessary.

Table 3.8. Window thermal transmittance boundary condition

WINDOW TYPE	THERMAL TRANSMITTANCE (W/M² · K)
METAL SASH SINGLE GLAZING	5.60
METAL SASH DOUBLE GLAZING	4.65
RESIN SASH DOUBLE GLAZING	2.91

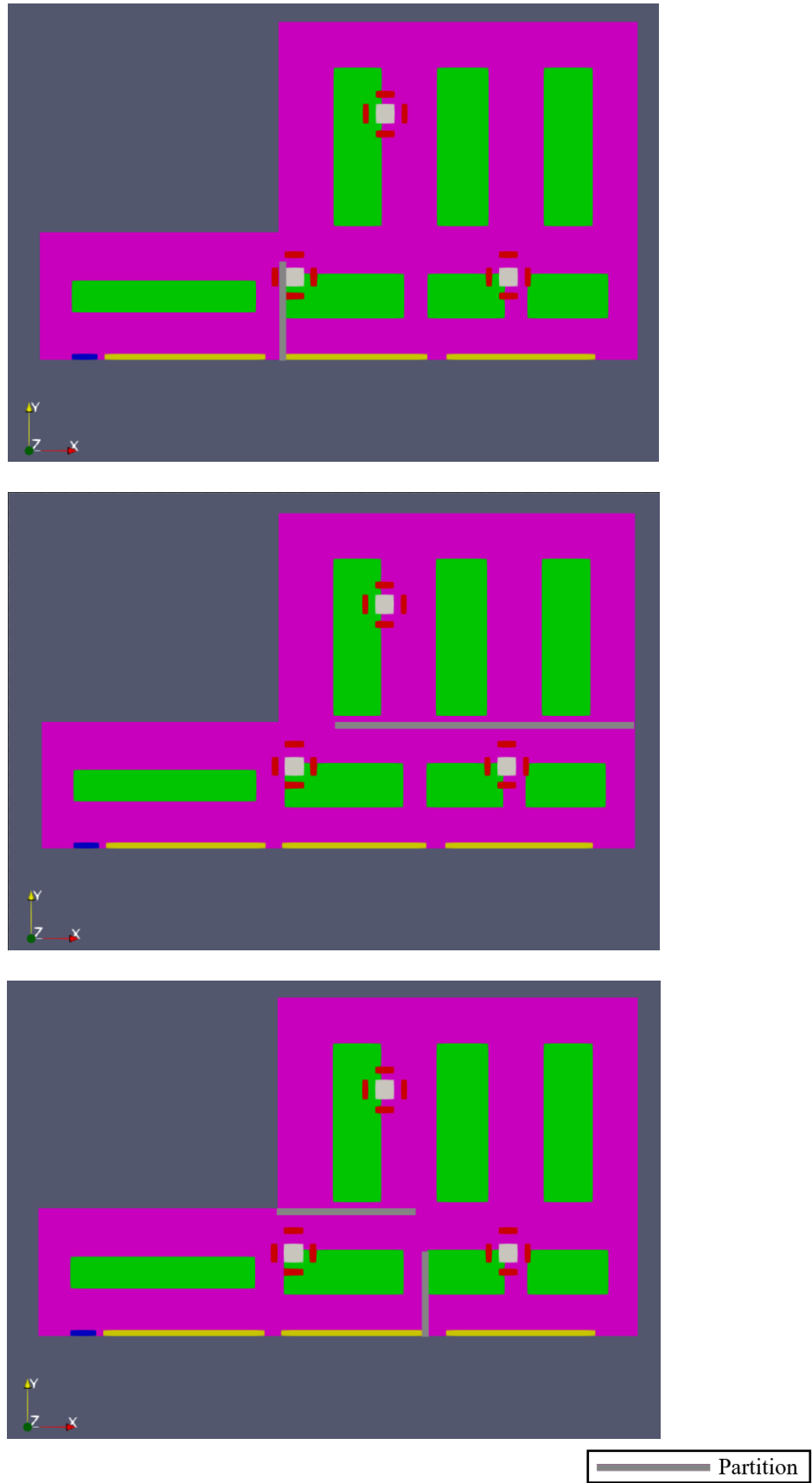


Figure 3.7. BlockMesh of three partition proposals (above: case a; middle: case b; bottom: case c)

3.3.6 Results

3.3.6.1 Numerical results

Combining 3 kinds of partition settings and 3 kinds of window designs, 9 situations were simulated in OpenFOAM in this chapter. The average temperature distribution of the CFD simulation results is shown in Figure 3.8. The results show that cases a3, b3, and c3 have higher temperatures than the other cases, indicating that the resin sash and double glazing helped to improve the indoor thermal insulation effect. The highest average temperature was for case c3, which was 3.37 °C higher than that of case a1 with the lowest average temperature. The temperature increased by 17.08% compared to the original data. In addition, the addition of the partition slightly improved the room temperature by improving the indoor air flow. The box plot of the average temperature results (plus positive and negative error values: 0.66) in Figure 3.8 shows that as the windows increase from single glazing to double glazing, the sash changes from metal to sash, and the average temperature gradually increases. Some data from the proposed improvement methods reported lower temperatures. Therefore, an experimental group without daylight was conducted. The results in Table 3.9 show that with the improvement of the sash and window, the average indoor temperature increased by the expected step. The reason for these results was that the metal sash can absorb the heat of daylight faster than the resin sash, and it will create the illusion that the indoor average temperature increases rapidly in the short time of the experiment. Therefore, the overall results were acceptable.

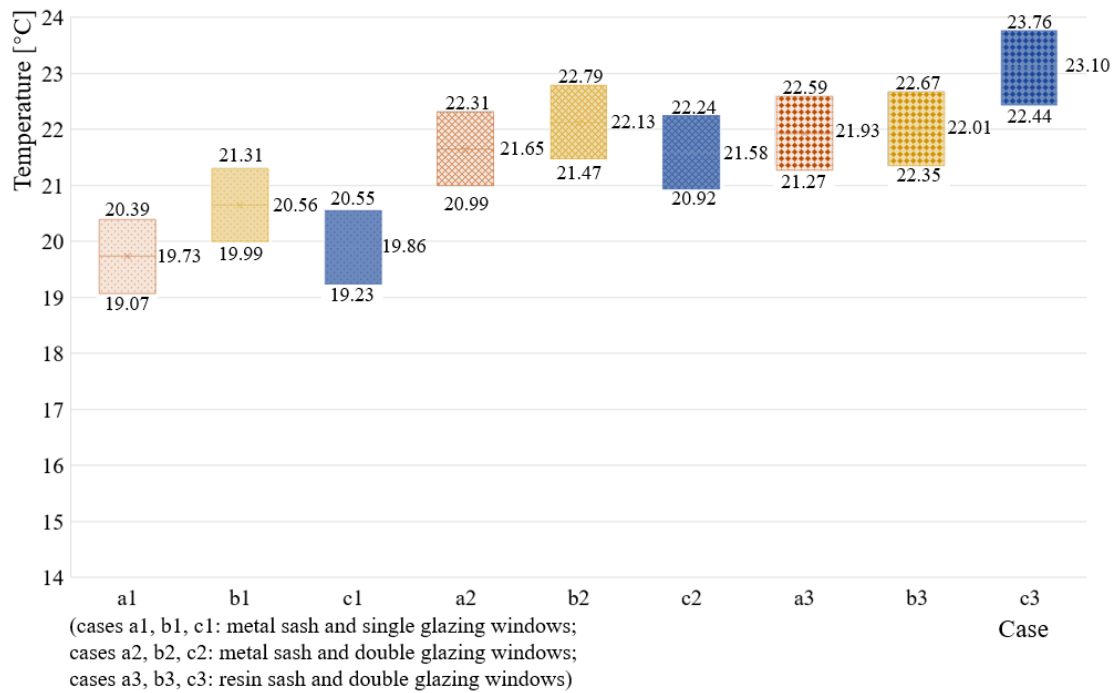


Figure 3.8. Average temperature distribution of the CFD simulation

Table 3.9. Experimental group results (without daylight) of the CFD simulation

ITEM	MATERIAL AND WINDOW TYPE		
CASE	a1 b1 c1	a2 b2 c2	a3 b3 c3
AVERAGE TEMPERATURE [°C]	16.94 17.63 17.67	17.76 18.26 17.75	18.83 19.61 19.64

(cases a1, b1, c1: metal sash and single glazing windows;
cases a2, b2, c2: metal sash and double glazing windows;
cases a3, b3, c3: resin sash and double glazing windows)

3.3.6.2 Visualization results

The proposed cases a3, b3, and c3 were the best window designs with the least heat loss. They were visualized by the proposed integrated system, which was installed on the HoloLens Gen 1 for further evaluation. The different renovation plans and visualization results of the indoor thermal environment were displayed by HoloLens. People without professional skills can intuitively understand the CFD results and discuss the visual impact of the new renovation plan. HoloLens is a wireless HMD; users can wear it indoors and move around freely. The CG animation dynamically

streams the indoor thermal environment, cycling through 12 frames of model changes, one frame per second, so that the entire process of temperature and airflow changes can be observed.

Figure 3.9 shows HoloLens screenshots showing the thermal environment in the areas around the three air conditioners at the beginning of the simulation; the streamline colors indicate the temperature gradient, and the streamline diameter indicates the airflow rate. Figures 3.10, 3.11, and 3.12 show different visual effects of the partition design in cases a3, b3, and c3, respectively. The viewing position and field of view are shown in Figure 3.13. These pictures show how the partitions affect the airflow and how the airflow goes around the partitions, changing the distribution of the indoor temperature. Figure 3.14 is a small scale model based on the CFD results of Room 411 in its initial state. It allows the viewer to see the immediate thermal changes in the environment as a result of the renovation. The occlusion was displayed correctly and the partitions set in different cases seemed quite real. The thermal environment was displayed dynamically, allowing users to experience the entire process of temperature and airflow changes. In addition, for those who have no background in environmental studies at all, the heat map and comfort map are integrated into the MR system. The heat map, calculated by CFD software and then post-processed by ParaView, is recorded in the real world. The result is shown in Figure 3.15. The three rectangular occlusions near the left ceiling light are the location of the air conditioner used in the calculation, and the occlusions around the bookcase and wall edges are generated in real time. Figure 3.16 shows the user's visual experience of the heat map combined with the small scale model of Room 411. Figure 3.17 shows the user's visual experience of the comfort map, where the comfort zone is colored blue and the discomfort zone is colored red. Referring to Figures 3.16 and 3.17, the user can easily know that the cause of the three circular red discomfort zones in Figure 3.17 is because the upper and lower temperature difference under the air conditioners is too large, and the corner red discomfort zone is formed because it is too far away to transfer heat from the air

conditioner in a short time. All of the above scenarios can be toggled by voice commands such as large (change to full scale), small (change to 1:10 scale), and change (change renovation plan).

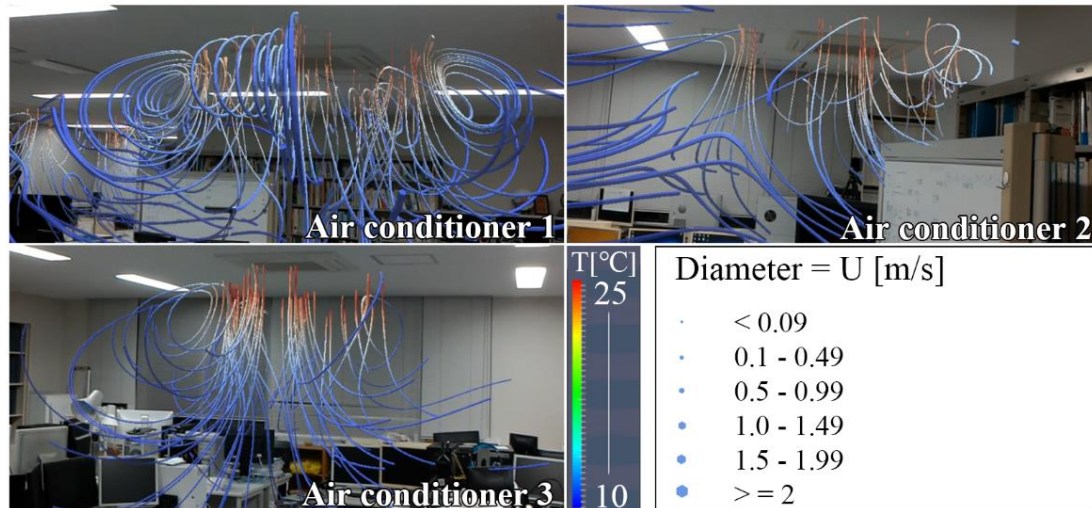


Figure 3.9. Thermal environment performance in the HoloLens

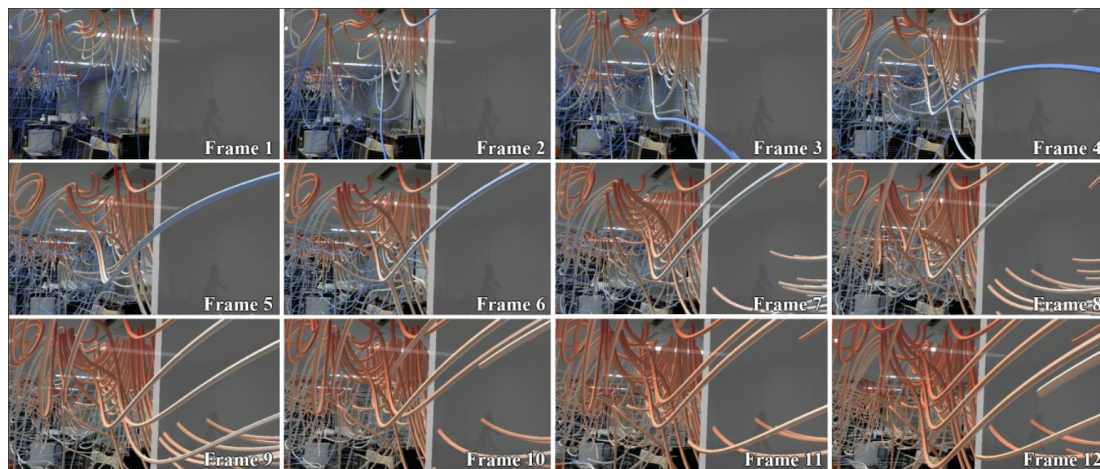


Figure 3.10. Animated CFD result of case a3 in the HMD (Gray board: New partition)

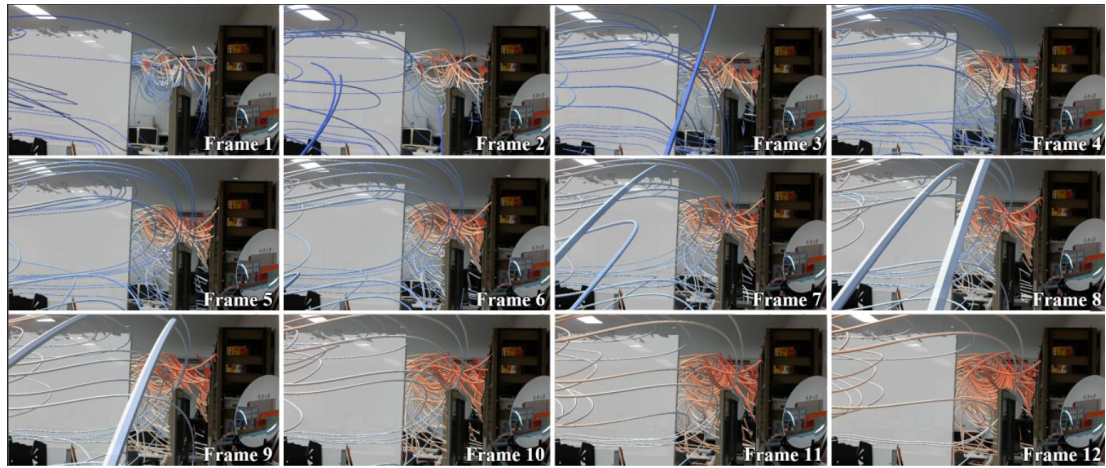


Figure 3.11. Animated CFD result of case b3 in the HMD (Gray board: New partition)

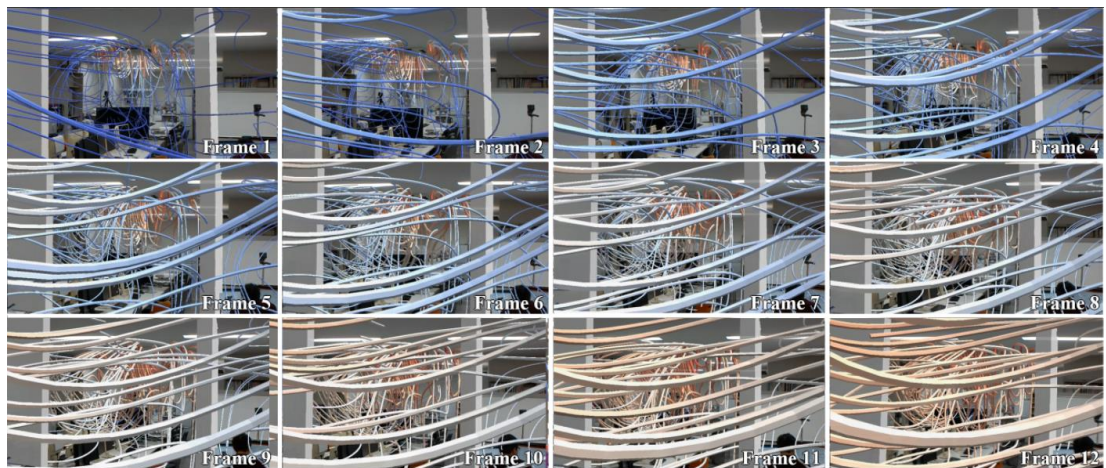


Figure 3.12. Animated CFD result of case c3 in the HMD (Gray board: New partition)

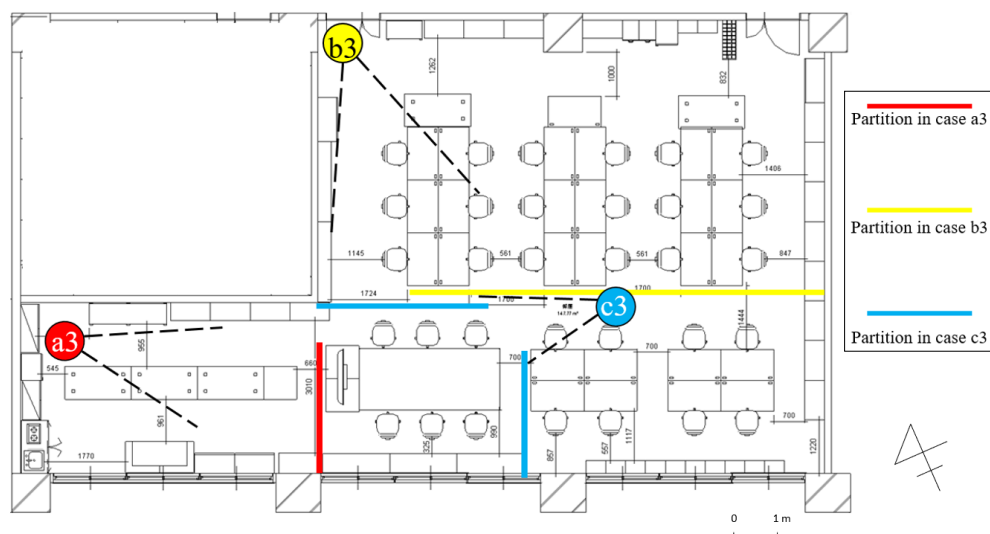


Figure 3.13. Observation position and field of view

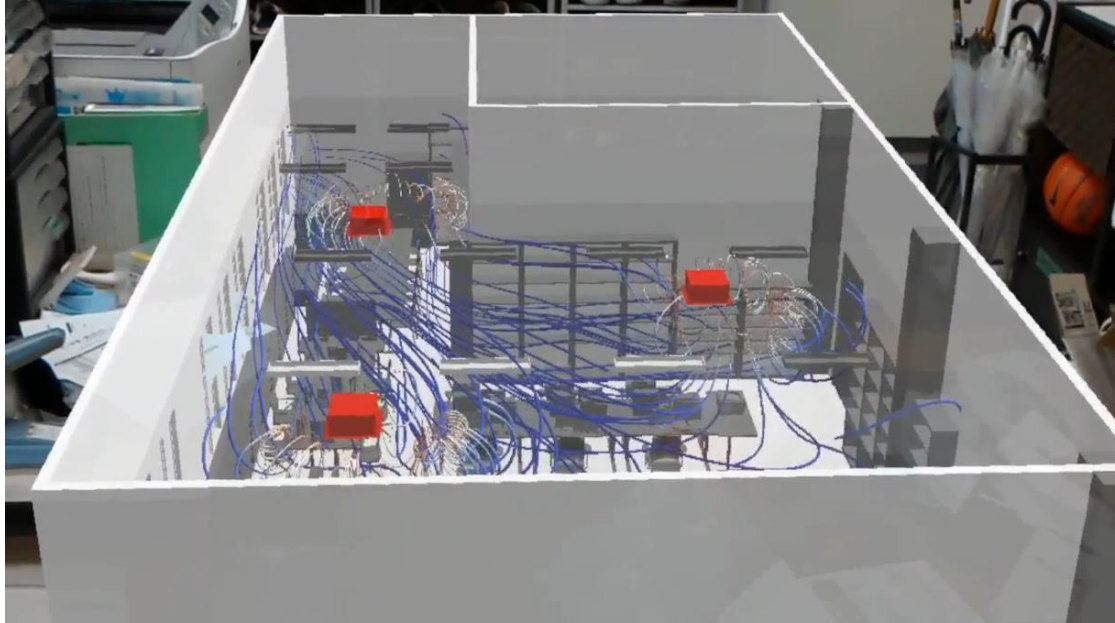


Figure 3.14. HMD view of room 411 small-scale model (1/10) using CFD results

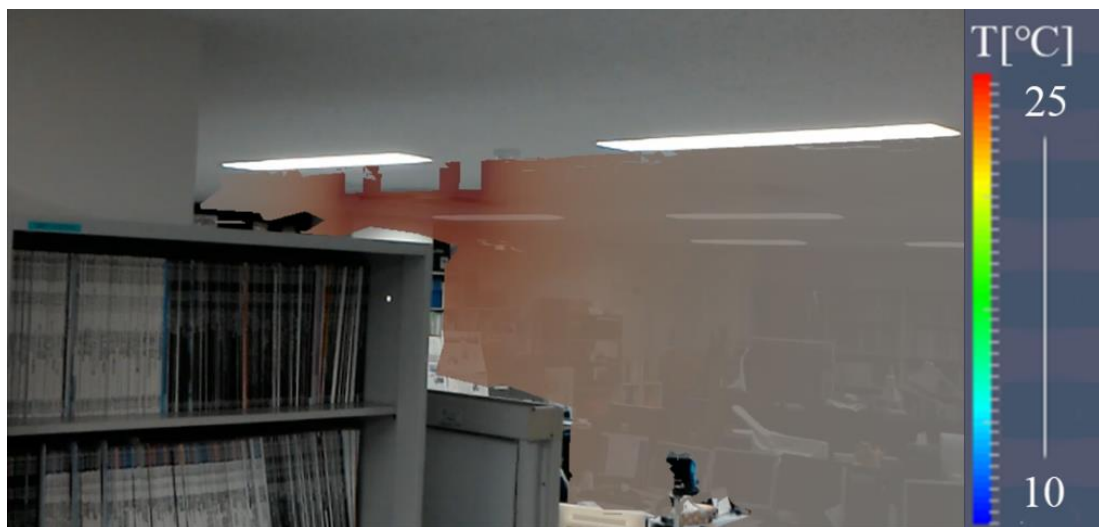


Figure 3.15. HMD view of indoor heat map



Figure 3.16. Heat map of room 411 small-scale model (1/10)

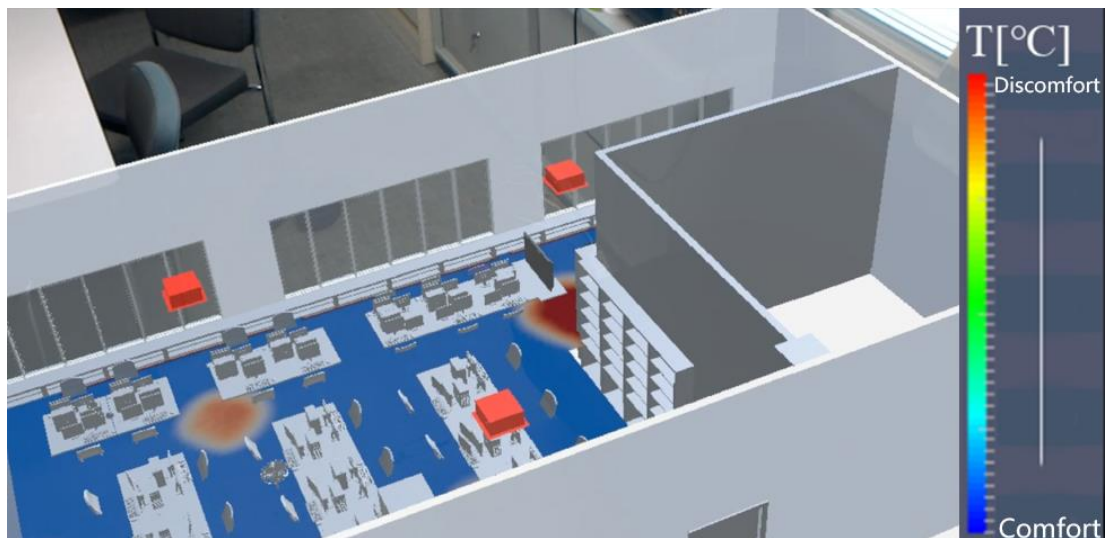


Figure 3.17. Comfort map of room 411 small-scale model (1/10)

3.4 Discussion

In conventional renovation projects, the building design process tends to be inefficient because the client does not fully understand the designer's intention. Therefore, this study attempts to solve the problem by building an MR system that integrates CFD results to allow users to visualize indoor temperature and airflow using the HMD. CFD animation provides a clear visualization that is straightforward, easy to understand, and

conveys information directly to the user. A good evaluation method is critical in the building design process because designers usually propose more than one renovation design. In a typical design process, there is a lack of coordination between designers from different departments. Therefore, there is a need for an evaluation method that is accurate, fast, and easy to understand. When presenting renovation plans to stakeholders, the expertise of different departments is not linked. Therefore, the method proposed in this chapter can visually display all the necessary information, which strengthens the communication between different departments, and new proposals can be presented in a short period of time. In this chapter project, the CFD results were first presented on HMDs as full-scale models to allow viewers to experience the superposition of virtual objects in the real world. However, it was found that in some cases, viewers could understand a phenomenon more quickly using a small-scale model rather than a full-scale model. Therefore, a voice-controlled conversion function between two models was added to this system. In the small-scale model, viewers can quickly understand the entire indoor thermal condition; however, compared with the full-scale method, this method replaces the real indoor environment with the BIM model, causing viewers to lose their relationship with reality and a lack of immersion.

CFD analysis requires many resources and real time calculation: a future research topic for investigation. The average computation time for CFD analysis in the case studies was 68 minutes and 38 seconds for PC (B) and about 20 minutes of manual operation for PC (A). Powerful computers can significantly reduce the computation time for CFD. After the publication of this chapter, a method has been proposed that uses mobile devices for 3D environment scanning and manual input of environment parameters, while high performance servers perform the environment analysis. The system adopts a client-server architecture that can achieve near real time output of CFD results (Chae et al., 2022). Alternatively, fast fluid dynamics (FFD), which is a real time technique, computes fluid visualization with computational speeds that are hundreds of times faster than CFD (Katsuno et al., 2011). Although FFD sacrifices accuracy, its real time

feedback has great potential for building design simulation. If real time feedback and evaluation are implemented, they will greatly increase the effectiveness of renovation design. Therefore, an FFD-based system is worth considering.

The disadvantage of HoloLens is that despite its field of view, which is approximately $30^{\circ} \times 17.5^{\circ}$ in Gen 1 and $43^{\circ} \times 29^{\circ}$ in Gen 2, the experience is like looking at the digital world through a small magic window in the center of the field of view. This experiment was conducted as a validation study with the HoloLens Gen 1. Although the HoloLens Gen 2 has an expanded field of view compared to the first generation, it still does not reach the generally comfortable range of human vision, which affects the immersive experience.

3.5 Summary of this chapter

In this chapter, an existing building renovation application using CFD analysis and MR technology was developed to enable the simultaneous design of the building plan and thermal environment during the renovation process. The proposed system provided an intuitive and efficient solution compared to conventional methods by using CFD animation and MR technology. Different partition designs, window designs, and glass materials were compared in the simulation, and the optimal proposal could be studied. After experiencing different renovation plans and comparing their pros and cons, people without professional skills could independently understand the design content and participate in the building design more easily. Owners are enabled to express their own ideas and then immediately discuss the design possibilities with design specialists within the MR system.

As future work, it is necessary to find an alternative optimization method to simplify the CFD animation generation process. At present, the process is a complex sequence that requires a lot of manual operation, which brings a lot of inconvenience to designers. In addition, the process of obtaining the CFD simulation results is also a time-

consuming operation. Since timely feedback is important for consensus building, a renovation design system that provides real time visualization information should be considered. If CFD simulation and animation can be performed in real time, the results of a proposed design can be experienced immediately, and design feedback is greatly improved. Therefore, using methods such as graphics processing unit (GPU) computation to accelerate CFD computation to real time standards, or changing the CFD simulation tool to a faster one, such as FFD, are topics for future work.

In addition to the current indoor Environmental Factors simulated in this study, there are many other factors, such as artificial light and sound, that are also necessary for building design. Adding these new factors to simulation systems will contribute to the improvement of renovation plans.

Chapter 4

An enhanced interior renovation design system using Mixed Reality: optimizing spaces with 360-degree streaming and Generative Adversarial Networks

4.1 Overview

DR is a specific technology that alters the user's perception of the real world by removing or hiding real objects from the user's visual environment (Cheng et al., 2022). Instead of adding digital content to the physical world as in traditional MR methods, DR technology uses various computational techniques to modify unwanted elements from a live video feed or real-world view. A practical application could be in interior design, where a user could virtually "remove" existing furniture from a room to visualize how new items might fit (Herling & Broll, 2014).

There are many ways to achieve DR. The key is how to generate the erased part, called the DR background in this chapter, and the quality of the DR result depends on it. In-painting is one of the methods that try to apply textures and patch details directly from the source image to paint over objects (Kawai et al., 2014; Kawai et al., 2015). Moreover, the more satisfactory the DR results, the more computational resources are required (Mori et al., 2020). On the other hand, in-painting methods are usually used to erase small and independent objects, and this approach may face limitations when

dealing with complex indoor environments (Kunert et al., 2019). In comparison, building structures, such as walls and columns, are relatively large objects that are connected to the environment. Therefore, it is difficult to use in-painting methods to erase large objects such as an entire wall.

Methods that use pre-recorded images or videos as background references also have limitations in displaying real time backgrounds and restrict users to the perspective of the pre-recorded images (Mori et al., 2015; Li et al., 2013). For authentic, large-scale DR, virtual background reconstruction is essential. This chapter used a deep learning method for background reconstruction.

GANs are a class of deep learning models introduced by Ian Goodfellow and colleagues in 2014. They consist of two neural networks, the generator and the discriminator, which are trained simultaneously in a competitive environment (Li et al., 2022):

Generator: This network takes random noise as input and produces data (like images).

Discriminator: It tries to distinguish between genuine data (from the training set) and fake data produced by the Generator.

During training, the generator tries to produce data that looks as real as possible to fool the discriminator. The Discriminator tries to get better at distinguishing real data from fake data. Over time, the generator becomes so good at generating data that the discriminator can barely tell the difference between real and generated data.

GANs have become particularly popular in computer vision, leading to significant advances in tasks such as image synthesis, style transfer, image super-resolution, and more (Tang et al., 2020a, 2020b; Andreini et al., 2020). The ability of GANs to generate highly realistic images and other types of data makes them a powerful tool in various applications (Zhang et al., 2022).

This chapter presented a novel method for generating a DR background capable of achieving realistic large-scale DR in real time.

4.2 Methodology

According to Figure 4.1, this system consists of four well-defined steps, namely real time data collection, background reconstruction (pre-process or run-time process), digitization of the rehabilitation plan, and system integration. A HMD is required that is equipped with a depth camera and an RGB camera, is capable of receiving Wi-Fi data, and has either its own operating system or the ability to exchange data with a computer in real time. After researching HMDs that meet these criteria, at the time of this study, only the HoloLens met these requirements, leading to its selection. However, if an HMD that meets these requirements is developed in the near future, it could also be considered for use. The system includes an HMD (HoloLens Gen 1), a 360-degree camera, a Wi-Fi router, and a computer with a GPU (Graphics Processing Unit) for processing GANs. The HoloLens Gen 1 has four "environmental understanding" cameras, an RGB camera, and a gyro sensor. This equipment can provide calibration information for registration and occlusion generation, as shown in Figure 4.2. The streaming data used to reconstruct the background is collected by a 360-degree camera placed in the center of the room to be renovated. These two devices communicate through a Wi-Fi router. Wi-Fi signals can pass through walls, making it possible to collect information in the adjacent room. The renovation plan is to build a BIM model that can provide professional information to designers, making it faster and easier for designers to modify the renovation plan. Synchronizing the BIM model with the 3D coordinates and occlusion information not only ensures the accuracy of the MR result, but also allows the user to have a more realistic MR experience. Except for some pre-processing, the entire MR system operates on the HMD, allowing users to view the MR results through its see-through display. From the user's perspective, the internal structures to be removed are reduced, the space behind the physical wall is displayed in

front of the user, and since the user can walk back and forth, the occlusion of the background space and the physical objects around the reduced wall are correctly displayed.

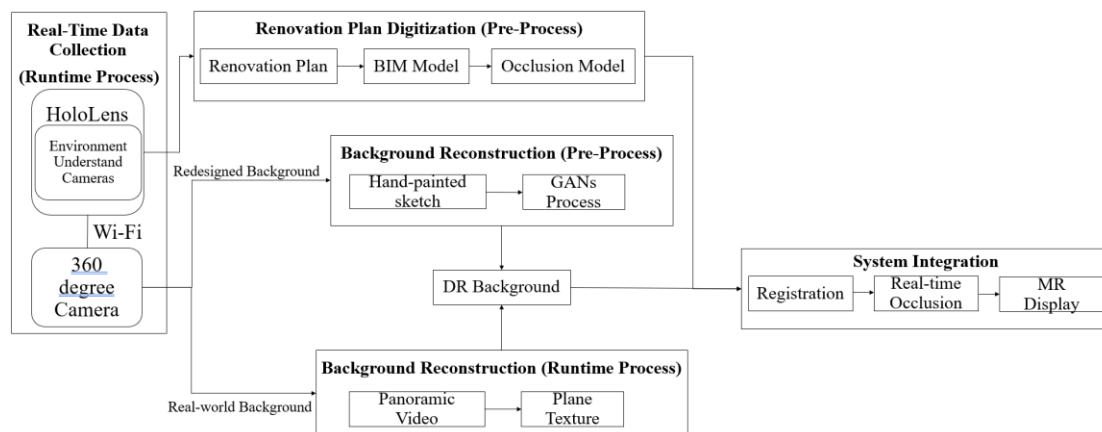


Figure 4.1. System overview



Figure 4.2. Wearing HoloLens Gen 1 (left); HoloLens Gen 1 appearance (right)

4.2.1 Real time data collection

Real time reconstruction of the background scene has become a key issue in recent research. Numerous DR methods based on in-painting methods have successfully achieved real time object exclusion. One such approach has realized a comprehensive image completion pipeline independent of pose tracking or 3D modeling (Herling & Broll, 2010). However, the results of these DR methods tend to be static, mainly targeting simple objects without complex patterns. This limitation is due to the fact that the background information largely depends on the characteristics of the immediate

environment. The complexity of the target object directly affects the predictability of the DR results: the more complex the object, the more unexpected the DR result. For this reason, in recent years there has been a surge in the adoption of methods that use 3D reconstruction for background scene generation. For example, the PhotoAR+DR project has advanced a reconstruction technique using photogrammetry software that generates a 3D background model by assimilating photographs of the surrounding environment (Inoue et al., 2018). The generated background is quite realistic, but processing can take up to ten hours or even several days. In a related study, another research team introduced a method for visualizing hidden regions using an RGB-D camera (Meerits & Saito, 2015). This method is capable of reconstructing dynamic background scenes. However, the data captured by the RGB-D camera is in the form of point cloud data. Due to their large size, these point cloud data files can hinder real time reconstruction, resulting in occasional delays or missing scene parts. To improve the consistency of DR results, researchers often find it necessary to thin the density of the point cloud data. This chapter presents a method for collecting background scene details using a 360-degree camera. Compared to standard RGB and RGB-D cameras, the 360-degree camera offers a wider field of view, allowing it to capture the entire background scene in one sweep. Importantly, the file size of the resulting panorama is much smaller than the large point cloud data, eliminating the need for mandatory wired connections for data transfer. In this study, the data size of the 360-degree camera is compact enough to facilitate wireless transmission. First, a plugin is developed using the API provided by the camera manufacturer. Then, a Wi-Fi connection is established between the HMD and the 360-degree camera. This connection is based on the `HttpWebRequest` class, with data typically retrieved and sent via GET and POST methods. Using this wireless connection, panoramic video can be streamed to the HMD in real time.

4.2.2 Background reconstruction

4.2.2.1 Panorama conversion

The proposed system receives panoramic video data byte by byte from the 360-degree camera and isolates the image of each frame from the data stream. However, directly using this original panoramic image to reconstruct the background would result in significant image distortion. To overcome this, it is essential to transform the panoramic image into a format compatible with the mask model to minimize distortion. The mask model acts as a 3D virtual representation of the target to be reduced and determines the segment of the virtual space for DR that is visible in front of the occlusion model. A 1:1 hexahedral space mask model is used to map the background image. The panoramic images are then segmented into six patches and applied to the hexahedron. The algorithm is influenced by a section of a VR study that explores the transformation of a cubic environment map (with 90-degree perspective projections on the face of a cube) into a cylindrical panoramic image (Paul, 2023). There are two primary solutions for slicing the panoramic image: one uses OpenCV image processing, and the other is based on OpenGL. The OpenGL approach adjusts the direction of the LookAt camera to obtain six textures, then reads and stores the resulting data. For the real time processing of panoramic images from the data stream required in this study, OpenGL methods could strain GPU computing resources, a known limitation of HMDs. Therefore, OpenCV methods are preferred.

4.2.2.2 Texture on the dynamic mask model

In this study, the background scene is not represented by a single image or model. Instead, a virtual room is created to replace the reduced wall. The mask model takes the form of a hollow cube with one side missing. The system continuously captures converted images that are dynamically mapped to the mask model, except for the diminished wall that is to be removed in the renovation design. The real time DR results

are then displayed on the mask model. Alternatively, one can switch to the rendered images generated by the pre-trained GANs and map them onto the mask model.

4.2.3 GANs generation

Enabling homeowners without design expertise to accurately articulate their design ideas has proven to be a challenge time and time again. These individuals cannot visually represent design concepts or build models the way professional designers can. They also rarely have the luxury of time to devote to these endeavors. Furthermore, relying solely on verbal communication often fails to effectively communicate their vision. In response, a strategy was developed to transform hand-drawn sketches into renderings. Based on an image-to-image translation technique first introduced in 2017 (Isola et al., 2017), a sketch-to-object model was trained. Given a training set of pairs of related images, labeled 'A' and 'B', the model can learn to transform an image of type 'A' (sketches) into an image of type 'B' (renderings).

4.2.4 Occlusion

Occlusion occurs when one object in 3D space hides another object from view. For a more realistic DR experience, physical objects should interact with virtual objects. Incorrect occlusion can make the DR result appear less realistic, as shown in Figure 4.3.1, while the real-world scene without virtual objects in the same position is shown in Figure 4.3.2. The system proposed in this study scans and generates real-world object occlusions in real time. It uses four "environment understanding" cameras from HoloLens Gen 1, which can sense the depth of the scene similar to an RGB-D camera. In addition, the system removes the real time occlusion of the wall it's intended to reduce. To ensure that the wall intended for DR isn't obscured by the occlusions detected by the "environment understanding" cameras, the scope of real time occlusion creation is limited. By limiting the scan area of the environmental understanding camera, the occlusion of the target wall is not created.



Figure 4.3.1. DR result without occlusion



Figure 4.3.2. Real world scene without virtual objects

4.2.5 System integration

Except for some pre-processing steps of GANs, which include model training and rendering image generation - performed on a computer equipped with the Ubuntu system - all other modules are integrated into the game engine. This engine supports

Universal Windows Platform (UWP) development. In particular, programs created using UWP are compatible with all Windows 10 devices, including the HMD HoloLens. Because of its support for UWP development and the inclusion of the development kit required for this experiment, Unity (2018.2) is used. The panorama conversion function is rooted in OpenCV (2.2.1), and its library must be imported into the Unity asset as an additional attachment package.

In order to validate the advantages of the proposed method, an evaluation was conducted in rooms 410 and 411 of the M3 building at the Suita Campus of Osaka University. Room 410 covers an area of 42.4 m², while room 411 covers an area of 150 m². The wall designated for the DR target was located between these two rooms, with dimensions of 6.5 m in length and 2.6 m in height. The observation points were to be concentrated mainly on the right half of the room (as shown in Figure 4.4). The 360-degree camera, THETA V, was positioned centrally in room 410. The overall arrangement is shown in Figure 4.4.

Figure 4.4. Room floor plan

4.3.1 System data flow

The system data flow for the DR function is shown in Figure 4.5. Two different sources provide the reconstruction data: GANs-generated renderings and images captured by the THETA V camera positioned behind the target wall. With this system, the user can choose between the actual scenario and the original design. Choosing the actual situation involves capturing the scene with a 360-degree camera and viewing it through the DR system. Alternatively, choosing the original design allows users to input hand-drawn sketches into GANs to generate the scene and then display it through the DR system.

In the pre-processing phase, the panoramic image is generated by a computer equipped with a GPU and then uploaded to the HoloLens. Numerous interior renovation renderings and their paired sketches were collected. Using edge extraction processing technology in Photoshop and a set of custom scripts, sketches can be efficiently derived from these renderings. By training the GANs network to transition from sketches to renderings, the sketches drawn by homeowners can be converted to renderings using this approach.

The captured panoramic video is streamed to HoloLens via a Wi-Fi connection. The transmission protocol is based on the THETA developers' API 2.1 (THETA DEVELOPERS BETA) (RICOH360, 2023). Within this method, the `HttpWebRequest` class is used to set the POST request. Then, the motion JPEG HTTP stream from the camera is parsed to generate each frame from the streaming data. OpenCV-based techniques are then used to transform these panoramic images into a hexahedral map, as shown in Figure 4.6.

Each frame is then mapped to a mask model as a texture and awaits processing. The digitization of the restoration plan falls under the MR segment, which provides both the restoration plan model and the occlusion. Once both parts are complete, the combined

results are projected onto a translucent screen in HoloLens. This allows individuals to "see through" the DR target wall. The real-world view of an individual experiencing the DR results can be seen in Figure 4.7. In Figure 4.7, the portion enclosed by the red frame represents the target wall. A portion of the target wall closer to the entrance is not selected for removal, primarily because of its structural importance.

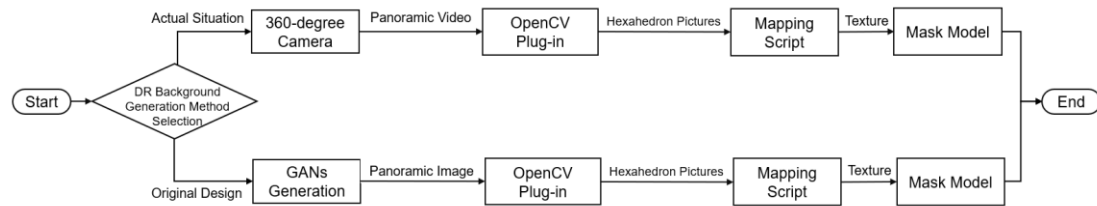


Figure 4.5. System data flow diagram

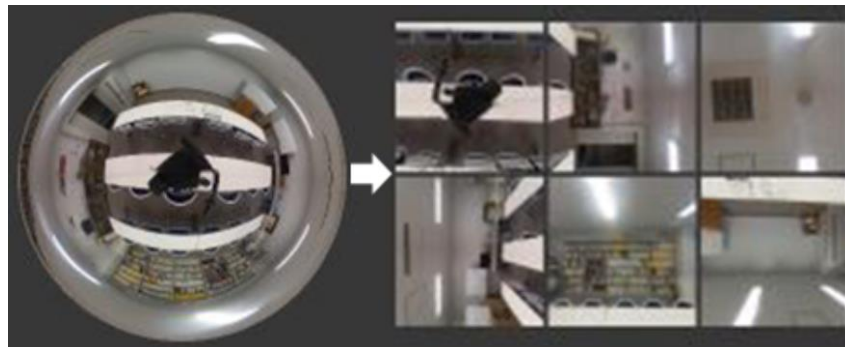


Figure 4.6. Panorama image conversion

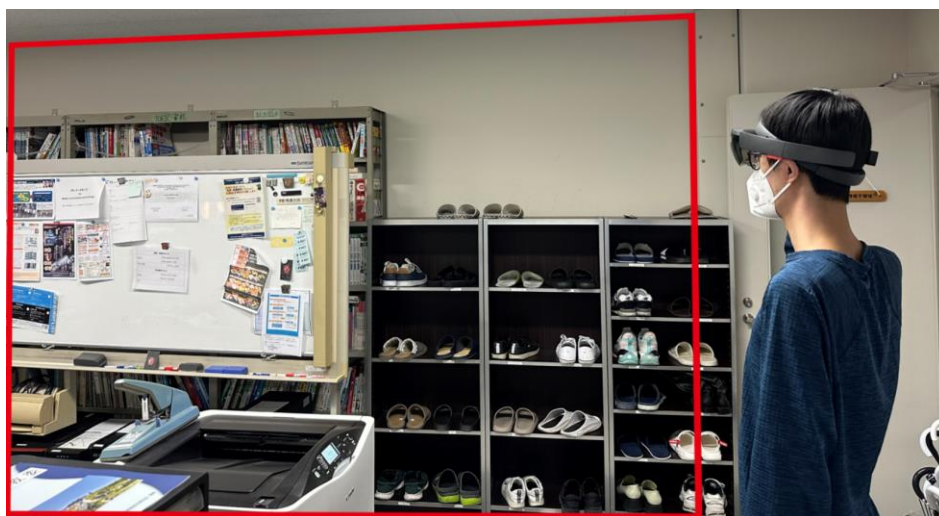


Figure 4.7. Reality view (Red frame: DR target wall)

4.3.2 Renovation target room

The BIM model, shown in Figure 4.8, can provide stakeholders with professional information and simplify the modification of the renovation plan. At the same time, to enable the MR system to operate on some older HMDs that lack real time scanning and environmental understanding cameras, the BIM model was used to generate mesh and collision created using Revit software. When the user wears the HMD for observation, the MR system needs to determine the user's position relative to the room. The BIM model facilitates this by assisting with registration, and when coupled with the collision data, occlusion can be calculated.

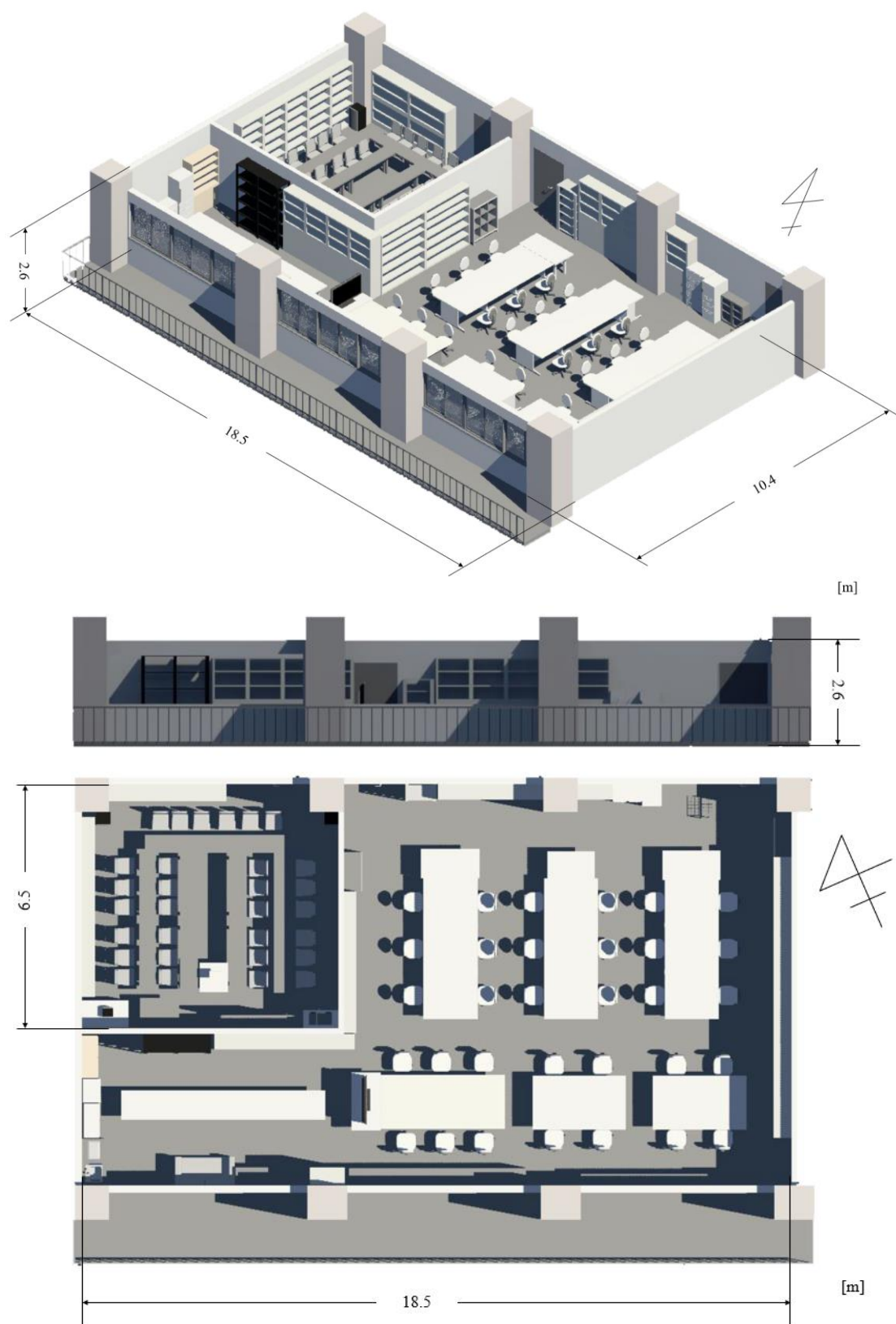


Figure 4.8. Room 410 BIM model

4.3.3 Operating environment

To verify the feasibility of the proposal, a prototype application was developed based on the methodology proposed in subsection 3.1. Including the BIM modeling, the development of the MR system, and the creation of the GANs training materials were carried out on a desktop PC (A) (specifications in Table 4.1). The GANs operations requiring CUDA and PyTorch and the installation of the dominant library ran on the Ubuntu system of PC (B) (specifications in Table 4.2). The GPU configuration requirements for PC (B) are relatively high. A GPU with lower specifications may adversely affect the computational speed of GANs, resulting in suboptimal performance in computational and processing tasks. The system environment setup for PC (B) is shown in Table 4.3.

Table 4.1. Desktop PC (A) specifications

ITEM	PERFORMANCE
OS	Windows 10 Enterprise 64-bit
CPU	Intel Core i5 7500 @ 3.40GHz
RAM	16.0GB Dual-Channel DDR4 @ 2400MHz
MOTHERBOARD	H270-PLUS
GPU	NVIDIA GeForce GTX 1060 6G

Table 4.2. Desktop PC (B) specifications

ITEM	PERFORMANCE
OS	Ubuntu 16.04
CPU	Intel Core i7 7700K @ 4.2GHz
RAM	16.0GB Dual-Channel DDR4 @ 2400MHz
MOTHERBOARD	Z270-K
GPU	NVIDIA GeForce GTX 2070s

Table 4.3. System environment of PC (B)

PACKAGE	VERSION
CUDA Toolkit Version	CUDA 10.0.130_410.48
Linux x86_64 Driver Version	NVIDIA driver 410.78
CUDNN	7.4.2.24
Anaconda3	2021.05
PyTorch	1.2.0
Pytorch Torchvision	0.4.0

4.3.4 Simulation of renovation proposal

To validate the applicability and effectiveness of the MR system proposed in this study, a simulation of the initial phase of a renovation project using the MR system was performed for rooms 410 and 411. As shown in Figure 4.4, the wall between rooms 410 and 411 was removed using DR technology to connect the two rooms. At the same time, a hand-drawn sketch was created by the participants as the renovation target for room 410. To facilitate the subsequent quality verification tests, the current configuration of room 410 (as shown in Figure 4.9) serves as the renovation target, prompting participants to create hand-drawn interpretations (as shown in Figure 4.10). These sketches are then entered into the PC (B). After processing by GANs, the generated renderings are loaded into the HMD, allowing participants to observe the simulated renovation results. Additionally, the current state of room 410 is captured by a 360-degree camera and wirelessly transmitted to the HMD in real time, allowing participants to manually switch between the two outcomes. For a more visual explanation of the experimental setup, the system scenarios are shown in Figure 4.11.



Figure 4.9. The current furnishings of room 410

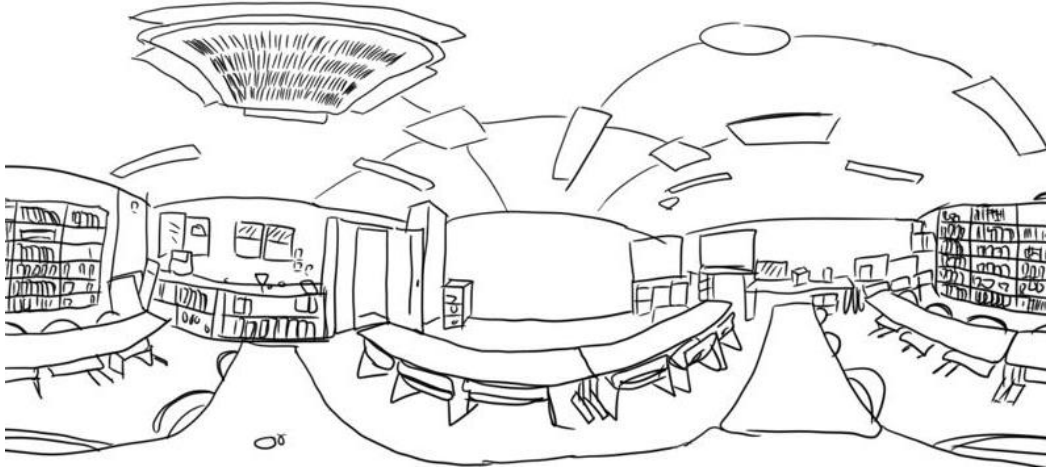


Figure 4.10. Hand drawn current furnishings of room 410

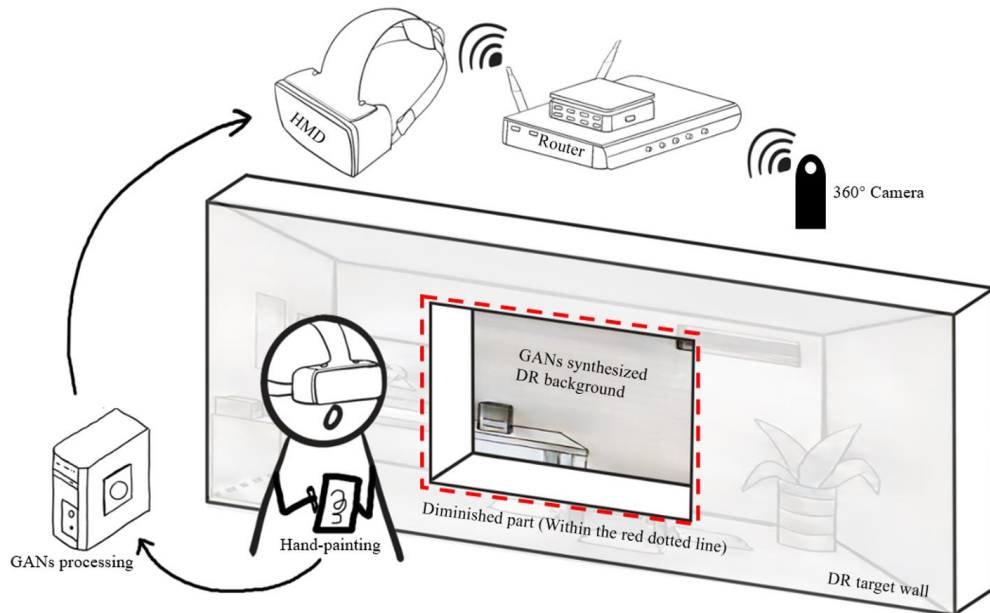


Figure 4.11. System scenarios

4.3.5 Verification of GANs generation quality

In the proposed simulation, 3044 pairs of panoramic images were input as the training data set. Among them, 2236 indoor panorama images were collected from the HDRIHaven indoor dataset (Poly Haven, 2023) and Shutterstock dataset (Shutterstock, 2023), and 52 indoor panorama images were captured by 360-degree camera. Of these, 52 images captured by the camera were subjected to data augmentation, including

flipping, scaling, and cropping. The available number was increased to 416. The paired sketches were also generated using a custom Photoshop script. Some of these are shown in Figure 4.12. In order to improve the quality of the renderings derived from the hand sketches, a set of 56 photos characterized by sensible layouts and non-repetitive styles was carefully selected from a pool of 2,236 interior panoramic images. These selected images were then subjected to hand drawing techniques. After data enhancement, a total of 448 paired training datasets were generated. Some of them are shown in Figure 4.13.

In order to quantitatively evaluate the quality of the panoramic images generated by GANs, this study intends to compare the results generated by GANs with the correct results. The correct results correspond to the existing layout of Room 410, as discussed in Section 4.4 of the thesis. In addition, nine interior panoramic images that are not part of the training dataset have been selected for verification. The evaluation uses the Structural Similarity Index Measure (SSIM) (Wang et al., 2004) and the Peak Signal to Noise Ratio (PSNR) (Huynh-Thu & Ghanbari, 2008). Both are related and complementary full-reference image quality assessment (FR-IQA) methods and are widely recognized as fundamental and universal image evaluation indices (Hor & Ziou, 2013).

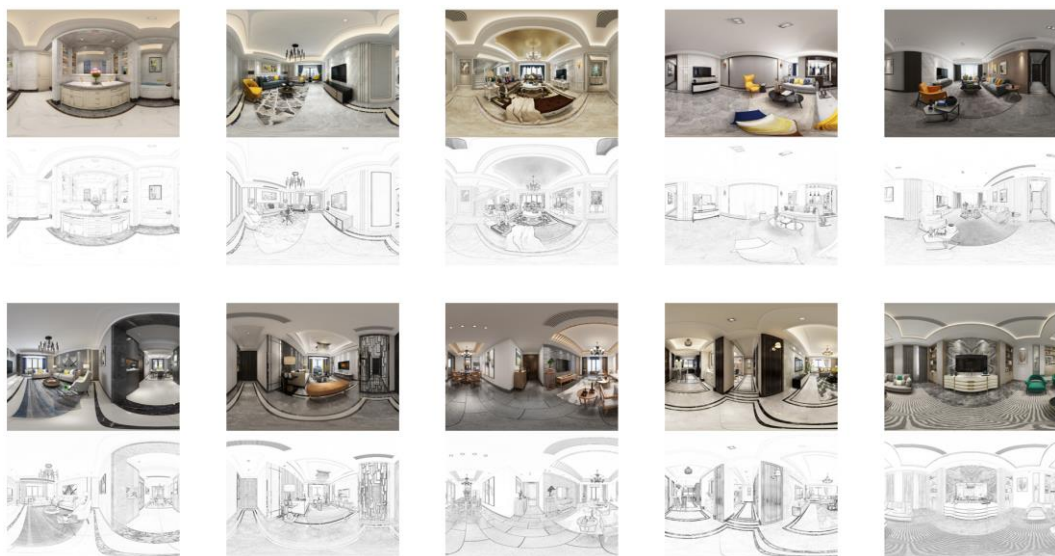


Figure 4.12. Part of the pairs' training data



Figure 4.13. Part of the augmented images with paired hand-drawing images

4.3.6 Numerical results

PSNR measures the relationship between the maximum potential value of a signal and the noise distortion that affects its representation quality. A higher PSNR value indicates better reconstruction (or compression) quality due to less distortion or noise. Conversely, a lower PSNR value indicates a decrease in quality. PSNR is expressed in decibels (dB). Based on general guidelines, the chapter can provide the following rough guidance (Jing et al., 2021; Cavigelli et al., 2017):

- Under 15dB: unacceptable
- 15-25dB: The quality might be considered poor, with possible noticeable distortions or artifacts.
- 25-30dB: Medium quality. Acceptable for some applications but might not be for high-quality needs.
- 30-35dB: Good quality, acceptable for most applications.
- 35-40dB: Very good quality.

- 40dB and above Excellent quality, almost indistinguishable differences from the original image.

The SSIM functions as an index to anticipate the perceived quality of an image in contrast to an original (reference) image. With its value range spanning from -1 to 1, an SSIM of 1 signifies that the test image matches the reference perfectly. As the SSIM value approaches 1, it underscores the increasing structural congruence between the two compared images. Here's a general interpretation of SSIM values (Horé & Ziou, 2013; Jing et al., 2021):

- $SSIM = 1$: The test image is identical to the reference. Perfect structural similarity.
- $0.8 < SSIM < 1$: High similarity between the two images.
- $0.5 < SSIM \leq 0.8$: Moderate similarity. There might be some noticeable distortions, but the overall structure remains somewhat consistent with the reference image.
- $0 < SSIM \leq 0.5$: Low similarity. Significant structural differences or distortions are present.
- $SSIM = 0$: No structural information is shared between the two images.

Numerical results to verify the quality of the simulated rehabilitation plans are shown in Table 4.4. The PSNR & SSIM values show that most of the images generated by GANs are of moderate quality and have a reasonable similarity to the correct result images. The image with serial number 1 was a hand-drawn sketch of room 410, while the rest were processed by scripts and manually corrected hand-drawn sketches. All results hover around 20dB, which is within an acceptable range. This indicates that the GANs methods have been effectively trained and can produce images that are both qualitatively good and structurally consistent with the expected results. While the quality of the GANs-generated restoration renderings may not be as good as

commercial renderings that require modeling and rendering processes, the low cost of a single hand-drawn sketch and its significantly faster generation speed compared to traditional renderings offer tremendous advantages in the early stages of the restoration process.

The results of GANs generated from training datasets with different numbers of images are shown in Figure 4.14. The more images used for training, the better the resulting image quality. In addition, as the level of detail in the hand-drawn sketches increases, the quality of the resulting image also improves.



Figure 4.14. Results generated by GANs with different training datasets: 50 images (top), 200 images (middle), 3044 images (bottom)

Table 4.4. PSNR & SSIM Scores for 10 Image Pairs

IMAGE NUMBER	1	2	3	4	5	6	7	8	9	10
PSNR (dB)	15.12	22.42	21.52	20.95	21.62	23.41	24.29	20.12	18.57	21.49
SSIM	0.7332	0.9265	0.8546	0.8956	0.8103	0.9187	0.9036	0.8452	0.8419	0.8516

4.3.7 Visualization results

As shown in Figure 4.15 the validation experiments captured DR result images at three different locations: A, B, and C. The original state of the target wall is shown in Figure 4.7, and Figure 4.16 presents the experimental results using the proposed MR system, showing 2D segmentation maps. Within these maps, the gray areas represent the real world objects, while the blue areas represent the background scene. The five planes of the mask model, as well as the walls, ceiling, and floor of Room 410, are seamlessly aligned in their real-world positions. As a result, users can accurately perceive the spatial sense of virtual room 410 as they move about. When viewed through the HMD, the DR results give the user the impression that the target wall has disappeared. In addition, activities in room 410 behind the target wall are instantly reflected in virtual room 411. The alignment function remains stable, ensuring that the virtual object is displayed without drift or disappearance.

However, occlusion isn't always accurately represented. We conducted a quantitative measurement of the accuracy of occlusion generation.

Intersection over Union (IoU) is a metric commonly used in computer vision, especially in object detection and segmentation tasks. It quantifies the degree of overlap between the predicted target area and the actual target area. The calculation of IoU (Intersection over Union) is shown in Equation (1). Simply put, IoU calculates the ratio of the intersection (the area covered by both the prediction and the truth) to the union (the total area covered by either the prediction or the truth) of these two areas. This ratio is between 0 and 1:

- 1) IoU = 0 indicates no overlap, where the prediction and the actual target are completely disjoint.
- 2) IoU = 1 indicates perfect overlap, where the prediction exactly matches the actual target.

$$(1) IoU = \frac{\text{Area of Overlap}}{\text{Area of Union}}$$

Typically, predictions with an IoU above a certain threshold (e.g., 0.5 or 0.7) are considered correct.

The comparative results of the captured images are shown in Figure 4.17. The pink area represents the correct no occlusion area, while the blue area represents the currently generated no occlusion area. The pixels in the area were measured, and the calculated IoU results are shown in Table 4.5. According to the IoU results, the accuracy rate is close to 80%. Although some of the occlusion errors can be clearly seen in the screenshots, the overall result is accurate and the error rate is acceptable.

Analysis of the segmentation map shows that parts of the occlusion edge are displayed incorrectly, and certain virtual elements that shouldn't be present in the DR results appear sporadically. This inaccuracy is due to the inaccuracy of the occlusion generated by real time scanning. The primary culprit is the lack of scanning accuracy. In addition, given the performance limitations of the HoloLens Gen 1, there are inherent systematic errors in the results. Beyond the uneven edge, the whiteboard that should be in front of the virtual room is obscured by the virtual components. Even though the distance between the whiteboard and the target wall is set for real time occlusion generation, the proximity between the two is so minimal that it occasionally leads to big errors.

In addition, the DR result is dynamic, but the refresh rate remains low. When testing this DR system on a PC platform, the process runs smoothly in real time. However, the

image transmission speed is limited by the bandwidth of the HoloLens, resulting in reduced frame rates.

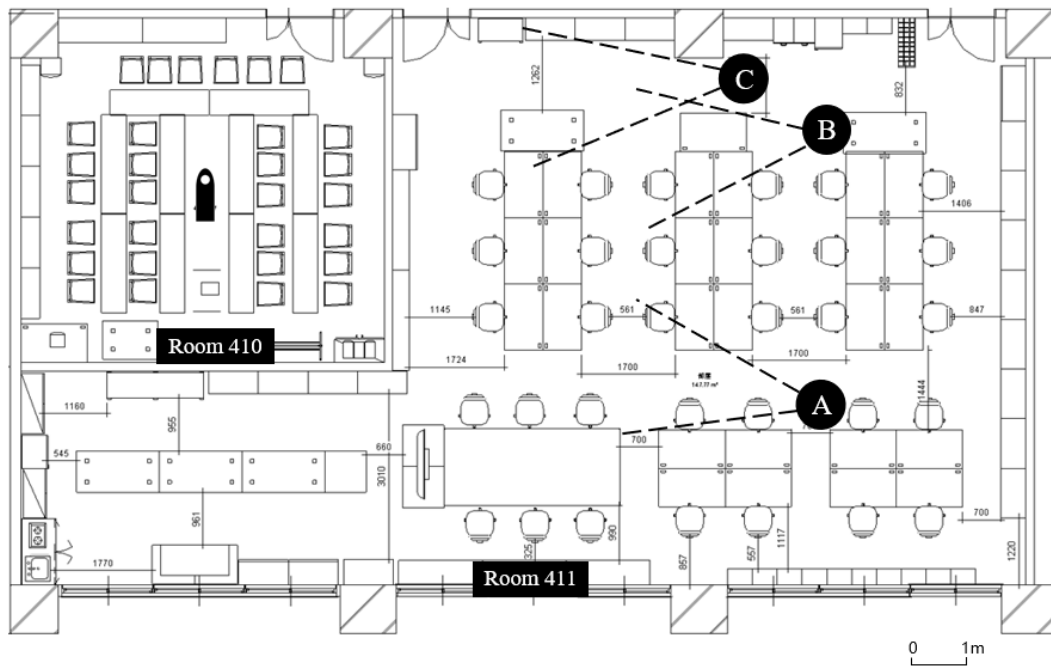


Figure 4.15. DR result capture locations



Figure 4.16. DR result and its segmentation map in position A (Above), B (Middle), C (Bottom) (Blue area as the mask region)

Table 4.5. IoU for DR result

ITEM\LOCATION	A	B	C
P (PINK) [PIXEL]	162280	146842	112951
B (BLUE) [PIXEL]	203644	181558	140171
$P \cap B$ [PIXEL]	161746	146080	112025
$P \cup B$ [PIXEL]	204099	182232	141035
IOU	0.7925	0.8016	0.7943

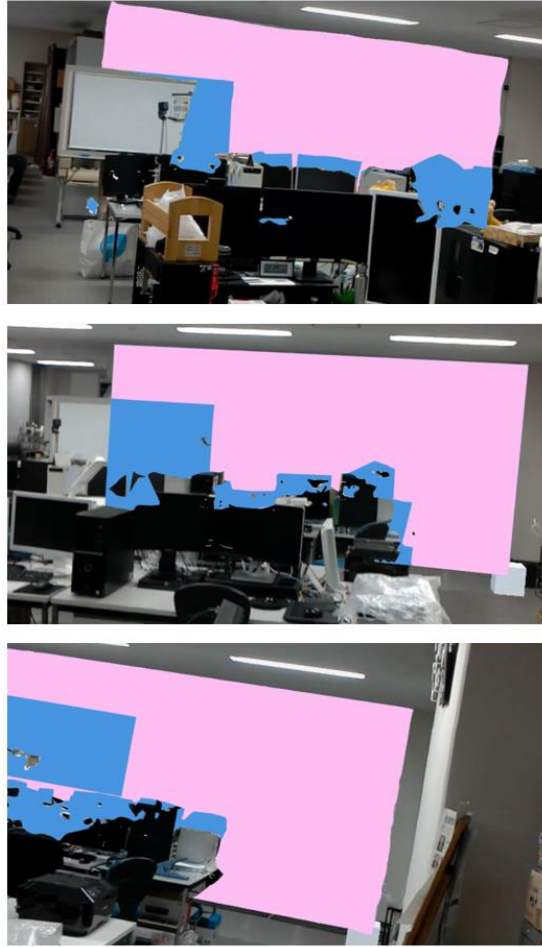


Figure 4.17. Comparison of correct (pink) and generated (blue) no occlusions area in position A (Above), B (Middle), C (Bottom)

4.4 Discussion

Using only algorithms to infer the background makes it difficult to create content for complex backgrounds, especially when there are no repeating patterns. Therefore, this chapter introduces the approach of using 360-degree camera data to reconstruct the background. Using a 360-degree camera allows for a quick scan of the entire DR background. Wi-Fi data transmission expands the range of deployment scenarios, ensuring that even in rooms with unique layouts, distance constraints are minimized and real time DR backgrounds can still be provided. This method is effective not only for complex backgrounds, but also for highly reduced targets. Especially for large DR

targets, there's no need for multiple cameras or multiple shots of the DR background from different angles. Panoramic images can more conveniently reconstruct the DR background. However, if the DR target is too large, the quality of the result may be compromised due to insufficient image resolution.

Although GANs-generated restoration renderings as backgrounds cannot compete with commercial renderings, the speed and low cost of hand-drawn sketches offer significant advantages in the early stages of the restoration process. What's more, the method of creating renderings from a simple sketch not only improves the efficiency of communication between designers and clients, but also increases the client's enthusiasm for participation. Even younger people can potentially provide valuable design insights. However, the direct creation of panoramic sketches by individuals without specialized artistic skills poses a challenge. To address this, an approach was developed using image processing software and a custom script to extract line art from rendered images. This method allows users to select preferred line art and then apply hand-drawn modifications based on these outlines. This facilitates the creation of panoramic hand-drawn sketches, allowing individuals without advanced drawing skills to create personalized artwork in their unique style.

In addition, using panoramic cameras to capture images or collecting royalty-free panoramas for training data sets is time-consuming and often results in inconsistent quality. Due to the lack of extraterrestrial data, methods for collecting training information on artificially constructed lunar terrains within a VR environment have already been presented (Franchi & Ntagiou, 2021). If the BIM model of a house is available, introducing it into a VR environment to collect panoramic images for training data is a viable approach. Compared to relying solely on basic data augmentation techniques, this method yields significantly higher quality training data. In addition, the models trained using this approach more closely match the style of the house before the renovation.

Latency challenges are common in streaming media transmissions. In this chapter, compromising video quality isn't an option, as a blurry virtual room would negatively impact the overall DR experience. The solution was to reduce the refresh rate. The program was manually adjusted to refresh the background. A button has been added to the user interface that refreshes the background when pressed. Another possible cause of latency is that the sampling rate of the sensors inside the HoloLens host is much higher than the frequency of regular wifi transmission, resulting in the HoloLens server buffer constantly holding a large amount of image data. As a result, the longer the socket connection time, the more data accumulates. This means that the longer the program runs, the higher the latency. Verification of this possibility can be done in future work.

4.5 Summary of this chapter

This chapter introduces a novel MR system that diminish wall to reveal real time details of the current background scene. Proper occlusion seamlessly blends the virtual and real worlds, enhancing the realism of the MR experience. This system allows designers to quickly modify renovation plans and visualize the effects. For occupants, the DR experience clarifies the designer's intentions and provides a vivid preview of the renovation results.

Currently, the system operates within a LAN. For future development, the creation of a relay server would enable WAN operation, allowing a remote room to be reconstructed for the user. During image conversion, segment parameters are manually set to ensure that wall edges are correctly aligned with the surfaces of the mask model.

In terms of the image quality produced by GANs, Figure 4.14 shows that as more training images are included, there's a noticeable improvement in the image quality produced. Although thousands of images have been used, the results still show a significant difference when compared to photos taken by cameras or rendered images. In future work, it's important to consider more efficient methods for generating training

sets. Manually created sketches are time consuming and costly, but yield the best results; scripted sketches are fast to produce, but the models trained from them aren't entirely adept at processing sketches drawn by non-professionals. In addition, GANs algorithms don't distinguish between panoramic images and regular photos in terms of learning and computation. However, for non-experts, making adjustments to renovation plans on panoramic images poses certain challenges. The approach in this study involves converting the images into cube maps for modification. However, this method is only suitable for small image changes. In addition, modifying parts located at the edge of the image is not straightforward due to distortion issues. This remains one of the critical challenges to be addressed in future work.

Recently, a number of AI tools have emerged that are capable of autonomously generating interior design plans (Mertayasa et al, 2023) (Sankar and Seitz, 2017). Using machine learning and computer vision technologies, these tools are able to generate interior design schemes based on input parameters or images. Some even offer real time rendering and VR previews, allowing users to experience design results more intuitively. They facilitate tasks such as creating floor plans, selecting furniture and decor, and adjusting colors and styles. However, these tools rely primarily on pre-trained models. While they quickly generate a variety of design proposals, they lack the ability to make specific adjustments based on user preferences, providing only inspiration and reference. In the future, if a fully functional AI automatic generation tool can be integrated, it may be able to solve the problem of the difficulty of inputting hand-drawn drawings by non-experts.

Chapter 5

Optimizing multi-users design for building renovation: integrating building information modeling and Mixed Reality with erased backgrounds

5.1 Overview

The use of BIM technology in co-design has emerged as a significant advancement in modern architecture and construction practices (Oh et al., 2015). BIM facilitates the process by creating digital representations of the physical and functional characteristics of a building. When integrated into the co-design process, BIM enables more effective collaboration and data sharing among stakeholders (Liu et al., 2017).

By using BIM in co-design, professionals from different disciplines can collaborate in real time, share updates, and make instant decisions based on the visual data provided by the model (Lai & Chang, 2019). This not only speeds up the design process, but also ensures that all stakeholders have a clear understanding of the project's progress and challenges.

In addition, the 3D visualization capabilities of BIM allow for a more intuitive design experience (Liu et al., 2015; Sun et al., 2019). Stakeholders can virtually walk through the design, allowing them to envision the outcome and suggest changes before actual

construction begins. This results in a more accurate and efficient design process, reducing the potential for costly modifications in later phases.

In summary, integrating BIM technology into the co-design process optimizes collaboration, enhances visualization, and streamlines the overall design workflow, ensuring better results and greater efficiency.

This chapter presents an advanced co-design approach that not only incorporates BIM information, but also seamlessly integrates it into the MR environment.

5.2 Methodology

5.2.1 Workflow

As shown in Figure 5.1, this system consists of three steps, namely background generation, shared network construction, and system integration. The equipment of the proposed system consists of several see-through HMDs, depth cameras, and a router.

The depth cameras can scan the environment to obtain point cloud data. The generated mesh can be applied to indoor renovation design projects (Fukuda et al., 2018). Using the collected data, a mesh of the scanned space can be generated. Since most of the surfaces in a real environment are not flat objects, models are manually constructed for them. Finally, using this mesh and 3D models, the virtual target room is created to meet the requirements of the DR background. The completed DR background is uploaded to each HMD and awaits registration and occlusion correction. All HMDs are connected via a wireless LAN established through a router, as shown in Figure 5.1. The HMD with code number one is used as a server to set up the port, and other HMDs are used as clients to connect to the host via the IP address and port number. The host will unify the initial coordinates of all clients by establishing a world anchor to synchronize the MR experience of all users. Finally, the occlusion is generated by each HMD through

the depth cameras in real time. Therefore, the DR result observed by each user may be a different perspective from his own viewpoint.

The entire MR system operates on the HMDs, where users can view the renovation plan through the see-through display, just as if they were communicating in a renovated room.

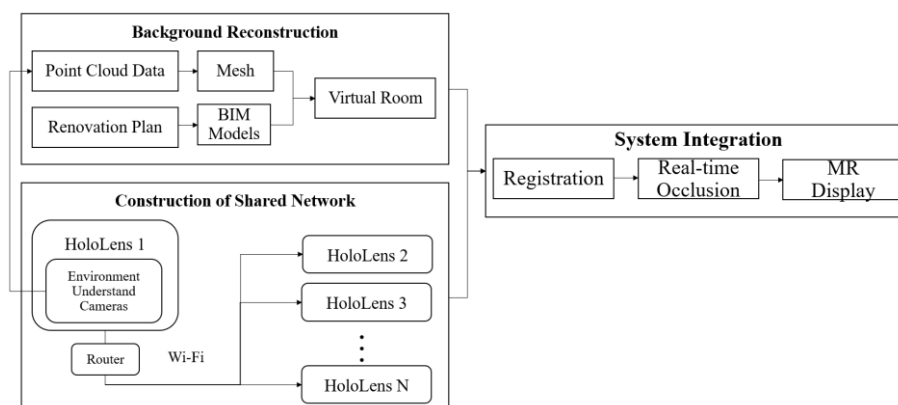


Figure 5.1. System workflow

5.2.2 Generating DR background

The creation of the DR background scene is divided into two parts: objects with basically flat surfaces (such as walls, floors, and bookshelves) and objects with a large number of polygons (such as tables, chairs, and chandeliers). Typically, the DR approaches are based on in-painting methods, which mainly rely on the algorithm to use the surrounding data to patch the DR target.

One of the approaches realized a complete image completion pipeline without relying on pose tracking or 3D modeling (Herling et al. 2010). However, the DR target is limited to simple and small objects without complex structures. Therefore, another type of DR approach called background observation uses pre-captured data of a background scene to reconstruct the DR background and has been widely used in recent years. An advanced 3D reconstruction system, which uses multiple RGB-D sensors to generate a stable triangle mesh, has been proposed (Meerits et al. 2019). However, due to the real

time generation, the generated result is coarse with many missing parts. Therefore, this method is suitable for small-scale, unidirectional reconstruction and observation.

In this study, depth cameras on the HMD were used to scan the room in advance as the DR background. This chapter uses HoloToolkit, which is a set of tools packaged by Microsoft based on the built-in API of the Unity game engine, to realize 3D space reconstruction based on the spatial mapping function. After using HMD to scan the target space, export the point cloud data file in obj format to the Unity project. In the Unity project, use the Object Surface Observer (Script) component in the SpatialMapping function to load the point cloud data, then use a shader to color and visualize the environment, then analyze the spatial mapping data to find the plane and remove the triangle, and finally use the plane to place the hologram. For some physical objects with a large number of polygons, or new objects proposed for the first time in the plan (there are no original objects and cannot be scanned), the chapter chooses to manually build the BIM model and import it into the MR environment.

5.2.3 Building shared network

Enhancing interaction during communication helps improve feedback efficiency. Encouraging occupants and designers to enter the same MR environment to evaluate the design plan and interact in real time is one of the important criteria of this study. The Unity component, Unet, is designed to convert single-player games into Unity multiplayer games (Unity documentation 2020). In a LAN established by the router, use Unet to make an HMD (No.1) the host and keep broadcasting. The world anchor for the initial coordinate point determined by HMD No.1 will be sent to the clients through the LAN to unify the coordinate system of all HMDs. In addition, if any virtual object, such as a desk and chair, is moved during the communication between the occupants and the designers, a new world anchor is added to the object, and its latest coordinate changes are transmitted to the host and unified to all clients.

5.2.4 Occlusion and registration

Occlusion occurs when an object is in front of another object from a viewpoint. Correct occlusion makes the MR experience more realistic and can correctly show the visual effects of the design plan to the experimenter. With correct occlusion, the virtual object interacts with the physical object, and the virtual world merges with the physical world to create the MR environment.

The incorrect occlusion makes the DR result unreal, as seen in Figure 5.2: left. For the occlusion with a higher frequency of change around the DR target, our proposed system uses depth cameras to scan the physical world occlusion in real time. At the same time, because the occlusion result generated by real time scanning is based on the user's field of view, for a relatively fixed large area occlusion, mask models must be added in the Unity project during pre-processing to achieve correct occlusion.

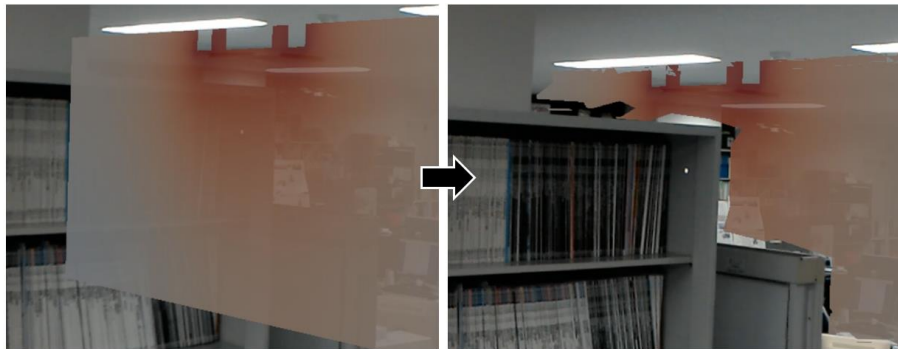


Figure 5.2. Left: Incorrect occlusion; Right: Corrected occlusion

5.2.5 System integration

Each module is integrated into a game engine, Unity, which supports UWP development. We use the Unity game engine to adjust the position, angle, and scale of the mesh, BIM models, and mask models to accurately place them in the MR system. In addition, programs developed using UWP can run on all Windows 10 devices, which ensures that the Unet network module can run on the HMD.

5.3 Experiment and results

5.3.1 System Evaluation

To validate the advantages of the proposed system, a case study was conducted in room 411 and room 410, M3 Building, Osaka Campus, Osaka University. The area of room 411 was 150 m² and that of room 410 was 42.4 m² (Figure 5.3). The equipment consists of a router (IEEE 802.11ac up to 867 Mbps; IEEE 802.11n up to 300 Mbps), a PC (i5-7500, 16GB DDR4, GTX1060,) for development, and two HoloLens Gen 1 with several environmental understanding cameras installed, including a depth camera, an RGB camera, and a gyro sensor (Microsoft HoloLens 2020).

In the case study, the renovation plan is to increase the field of view to connect the two rooms. As part of the plan, the proposed system will simulate a window on the wall, and the observers can see the effect of the virtual window on a wall with the correct perspective and occlusion, as shown in Figure 5.4. From the viewpoint of the observers, the part of the wall will be reduced, the room behind the physical wall will be displayed in front of the observers, and since the observers can walk back and forth, the occlusion of the background room and the physical objects around the reduced wall will be correctly displayed.

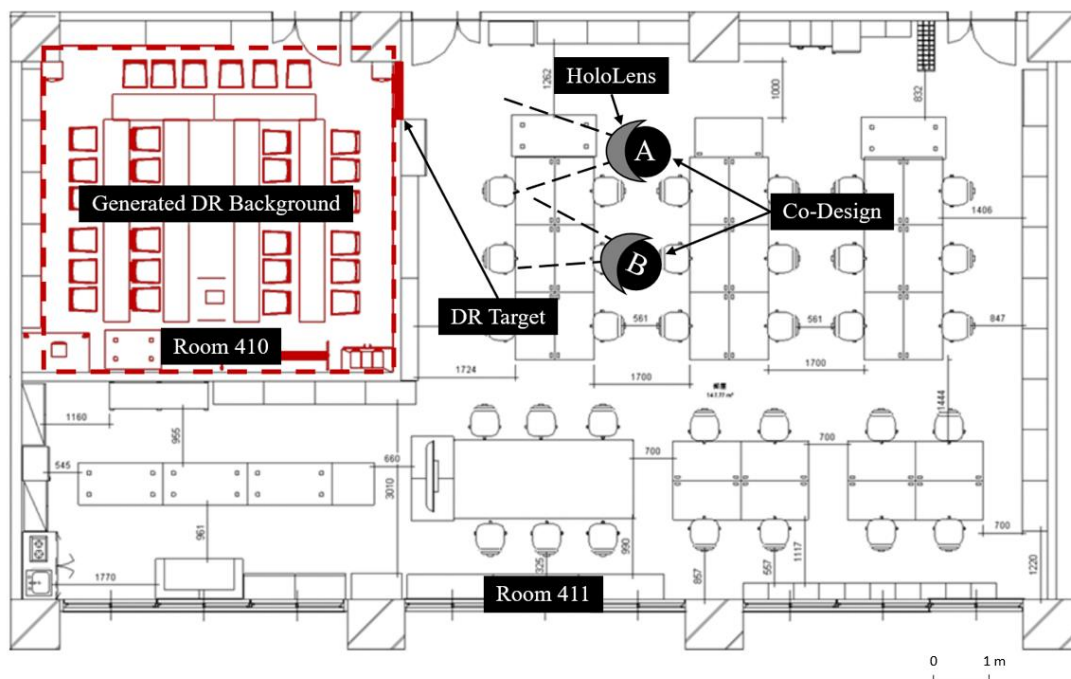


Figure 5.3. System experience scenarios

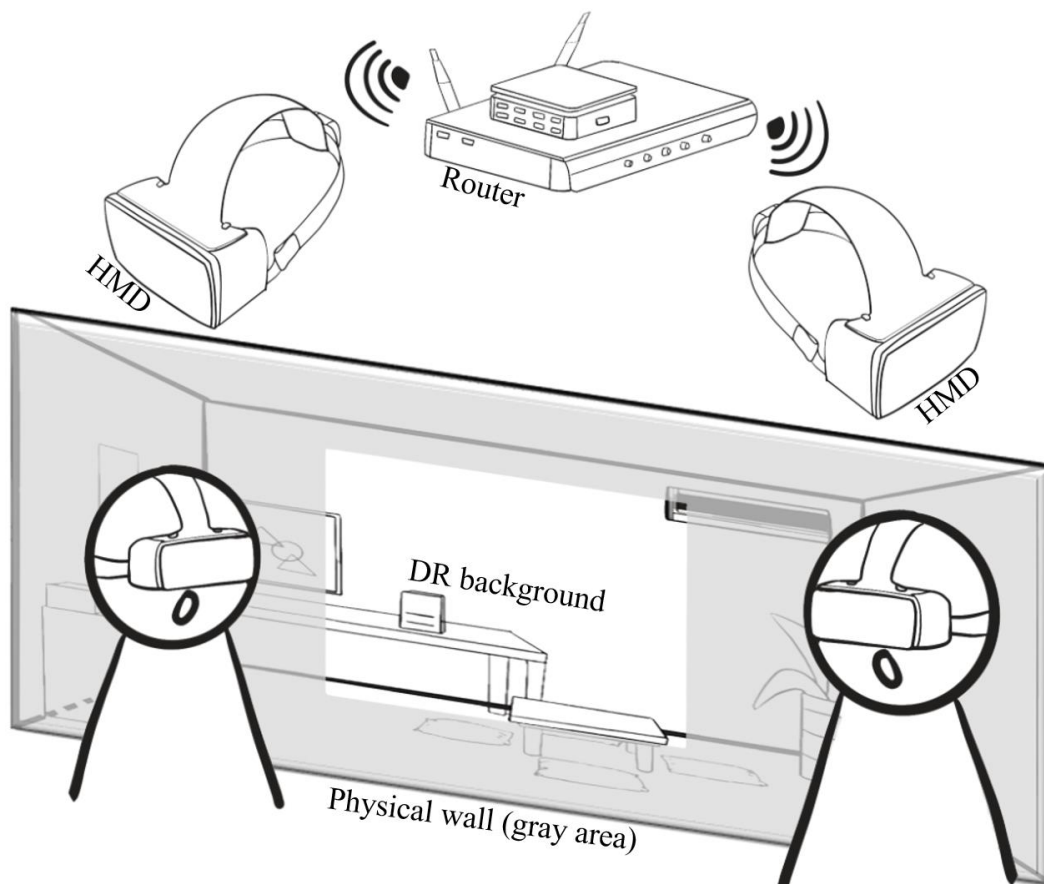


Figure 5.4. System experience scenarios

5.3.2 Visualization results

The observation area was set up in room 411, where two observers (A and B) can move freely around the room (Figure 5.3). The real scene of the target wall is shown in Figure 5.5, where the red frame shows the DR area. The experimental results using the proposed MR system are shown in Figure 5.6, which contains 2D segmentation maps, where the dark areas are real objects, while the blue areas belong to the DR background scene. The point cloud data generated from the mesh and BIM models of room 410 are coordinate coincident in the real world position. Therefore, when users view from different positions and angles, they can experience the correct perspective relationship between virtual room 410 and room 411. The DR area in Figure 5.5 viewed through the HMD makes users feel that the rectangular area has disappeared. Through the "window", users see the virtual room as if it were a real room. The registration function is stabilized, while the virtual object shows no drift or disappearance. Occlusion also contributes to a more realistic MR experience.

The two observers share the same MR environment, and the position, angles and occlusions of the design plans are essentially the same. During evaluation, users can easily move, rotate, and zoom the virtual objects within the MR environment, and all users can observe the entire surgical process.



Figure 5.5. Diminished target (room 411 real scene)



Figure 5.6. DR result (Blue area as the mask region)

5.3.3 Numerical results

To demonstrate the accuracy of DR background generation from a data perspective, this chapter conducted statistical analysis and measurements of the generated occlusion content. The widely used metric standard, IoU, was employed for the evaluation.

The Equation as previously mentioned (see Equation (1)).

In practice, this typically involves the following steps:

- 1) Identify the intersection region: This is the part where the predicted bounding box and the actual bounding box overlap.
- 2) Calculate the area of intersection: Measure the size of this overlapping area.

- 3) Determine the union area: This is the total area covered by both the predicted and actual bounding boxes.
- 4) Calculate the area of the union: This is the total area covered by the two bounding boxes minus the intersection area (since the intersection is counted twice in the union).
- 5) Calculate the IoU value: Divide the intersection area by the union area.

The IoU value ranges from 0 to 1, with higher values indicating a greater degree of overlap between the predicted and actual bounding boxes. In object recognition tasks, the IoU is often used to determine the accuracy of predictions. In general, in object recognition tasks, if the IoU value exceeds a certain threshold, such as 0.5 or 0.7, the predictions are considered accurate.

As shown in Figure 5.7, the pink area represents the correctly drawn manual unobstructed region, while the blue area represents the real time unobstructed region displayed during the MR experience in this chapter's experiment. The lower half of the image contains a significant number of incorrectly occluded areas, and preliminary assessment suggests that the problem may be due to the shoe cabinet being too deep, preventing the depth camera from scanning its interior. The pixel statistics for all areas and the IoU results are shown in Table 5.1. The results show that the generated occlusion positions have an average accuracy of 83%. Although there are some deficiencies in edge details, the overall accuracy is generally correct. Increasing the number of preliminary depth camera scans should yield more accurate results.



Figure 5.7. Comparison of correct (pink) and generated (blue) occlusions

Table 5.1. IoU for DR result

ITEM\LOCATION	ABOVE	MIDDLE	BOTTOM
P (PINK) [PIXEL]	24252	43421	68222
B (BLUE) [PIXEL]	28724	46457	68566
$P \cap B$ [PIXEL]	23112	41441	64511
$P \cup B$ [PIXEL]	29834	48368	72237
IOU	0.7747	0.8568	0.8930

5.4 Discussion

As described in Section 5.2.1, the proposed MR system can present the renovation plan as a virtual model during the pre-processing stage and then add real time occlusion and registration components, sharing the plan with all participants simultaneously using HMDs. In this MR environment, participants can observe each other's behavior, move or zoom virtual objects, add new designs (prepared model), and even remove a wall and throw it on the floor (requires pre-processing). Sharing visions, listening to design plans and expressing opinions will enable others to understand your ideas more quickly. In addition, if necessary, the proposed system can invite more participants by increasing the number of HMDs.

However, there are still some problems to be solved. Due to the hardware performance limitations of HoloLens Gen 1, the generated mesh contains systematic errors, and the transmission speed is limited by its bandwidth. This reduces the frame rate. Insufficient hardware performance is also one of the reasons why the DR background is generated in the pre-processing stage instead of in real time. Since data capacity and bandwidth affect the frame rate of the HMD, the real time generation method is abandoned to achieve a smooth experience. Another solution is to compress the point cloud data in real time, but this has not yet been implemented. After this experiment was completed, Microsoft Corporation released HoloLens Gen 2, which boasts improvements in hardware performance and software algorithms. Scanning for meshes should result in fewer errors. Specific verification may be conducted in future work.

5.5 Summary of this chapter

This chapter introduces a novel MR system integrated with DR functionality that enables interactive, real time communication among multiple users. Designers benefit from the intuitive presentation of design concepts within the MR environment,

providing clear insight into renovation intentions. Occupants, on the other hand, gain a comprehensive understanding of proposed renovations, allowing them to make simplified changes for easier evaluation of design aspects. However, the practical impact of the system has not been fully verified. Further research is needed to assess how this system enhances the effectiveness of collaborative design. Subsequent efforts will include detailed questionnaires and quantitative assessments to thoroughly evaluate the system.

Currently, the system operates on a LAN with a limited user capacity of two. Its scalability to support multiple users is a concern, potentially affecting performance metrics such as network load, data processing capabilities, and overall system stability. Scaling to support more users would require network optimization and data compression strategies, especially considering the increased data transfer. Future work aims to establish a low-latency, multi-participant MR environment with a focus on data compression and network optimization. In addition, plans include extending LAN capabilities to the WAN for remote sharing and implementing more complex modification methods and interactive gestures.

Chapter 6

Conclusions

6.1 Summary

This research has successfully developed a comprehensive MR system for retrofitting existing buildings, integrating CFD analysis and MR technology to facilitate the simultaneous design of building plans and thermal environments during retrofitting processes. Subsequently, the implementation of GANs allows residents without professional skills to participate in the design process using hand-drawn sketches. At the same time, the integration of Wi-Fi facilitates the connection of multiple HMDs, supporting a synchronized experience for multiple participants. The system is divided into three main stages:

Design and simulation: The system provides an intuitive and efficient solution for renovation design using animated CFD and MR technology. It allows the comparison of different design elements such as partition designs, window layouts and glass materials within the simulation, enabling the identification and study of the optimal design proposal. This immersive experience enables non-specialists to understand design concepts and become more actively involved in the building design process.

Modification and visualization: A novel MR technology is introduced to reduce walls with the DR function, display background details, and seamlessly blend virtual and real

worlds through proper occlusion, enhancing the realism of the MR experience. Meanwhile, a GANs method has been developed to help users who find it difficult to visually represent design concepts and construct models like professional designers, transforming hand-drawn sketches into more detailed and visually rich renderings. This functionality allows designers to quickly modify renovation plans and visualize the effects, giving occupants a clear preview of the renovation results and clarifying the designer's intentions.

Interactive communication and evaluation: The multi-users system supports interactive, real time communication between multiple users, allowing designers to intuitively view design concepts in the MR environment while helping occupants fully understand these concepts and the intended renovation results. Both parties can easily make changes to the renovation plans, facilitating the evaluation process and better weighing the pros and cons of the design.

6.2 Research contributions

To enhance the efficiency of the initial stages of the stock renovation, this study proposes several innovative methodologies:

Innovative integration of CFD analysis and MR technology: The research has successfully developed a system that uniquely combines CFD animation and MR technology. This integration enables the presentation of CFD results as 3D model animations within an MR environment, and facilitates the simultaneous design and evaluation of the building plan and thermal environment, thereby increasing the efficiency and effectiveness of existing renovation processes.

Intuitive design and simulation tools for non-professionals: The system provides intuitive and easy-to-use tools that enable people without professional skills to understand complex design concepts and actively participate in the building design

process. Users can navigate independently using voice commands and understand design content through immersive simulations and comparisons of different design elements generated from hand-drawn sketches to GANs.

Real time DR and pre-processed modification: The MR system presented in this study allows for real-time DR and pre-processed modification of restoration plans. Users can see the immediate effects of changes to occlusal elements, providing a clear and vivid preview of the restoration results. For the restoration plans of the reality parts deleted by DR, the pre-processing by setting masks and generating GANs allows users to observe and evaluate from different angles and positions. This feature not only improves the design process for professionals, but also demystifies the renovation results for residents.

Enhanced interactive communication and collaboration: The system uses multiple HMDs connected via Wi-Fi to enhance the user experience. It promotes real time interactive communication and collaboration among multiple users, including designers and occupants. This ensures that everyone involved in the renovation process is on the same page, resulting in a more inclusive and participatory design process.

Facilitation of quick design iterations: The system enables quick and easy changes to renovation plans, allowing designers and occupants to iteratively evaluate different design options. This rapid iteration process ensures that the best possible design is selected based on comprehensive evaluations.

In summary, the system enables quick and easy changes to renovation plans, allowing designers and occupants to iteratively evaluate different design options. This rapid iteration process ensures that the best possible design is selected based on comprehensive evaluations. By using this MR system, occupants are not just passive observers, but active participants in the design process. They can contribute their ideas

and engage in immediate discussions with design professionals, resulting in more user-centered and satisfying design outcomes.

6.3 Limitations and future research

Although the proposed method for stock renewal offers new opportunities to facilitate communication among stakeholders, it is important to recognize and address some limitations in future studies, as follows:

Complexity in CFD animation generation: The current process of generating CFD animations is complex and requires extensive manual operations, which can be inconvenient for designers. In future work, the researchers plan to explore alternative optimization methods to simplify this process and reduce the need for manual operations, with the goal of making the system more user-friendly and efficient.

Time-consuming CFD Simulation: Obtaining results from CFD simulations is a time-consuming process. To address this, future efforts should be directed at implementing methods such as GPU computation or switching to faster simulation tools such as FFD to enable real time CFD simulation and animation. This would greatly improve timely design feedback and the overall efficiency of the retrofit design process.

Limited system operation within LAN: The system is currently limited to operation within a LAN, which can limit remote collaboration and room reconstruction. Future development should include the creation of a relay server to enable Wide Area Network (WAN) operation, facilitating remote access and collaboration.

Manual setting of segment parameters: The formats, sizes, and content of the images used for training are chaotic. The need for manual adjustments during image conversion to ensure proper alignment can be cumbersome. Future improvements could focus on automating this process to reduce the manual workload and improve the usability of the system.

Challenges with image quality from GANs: The image quality generated by GANs, while improved with extensive training sets, still shows a significant difference compared to camera-taken photos or rendered images. To address this, future work should investigate more efficient methods for training and improving GANs algorithms, especially for handling sketches drawn by non-professionals and for handling panoramic images.

Challenges in panorama image modification: The current method of converting images into cube maps for modification is limited and can struggle with image distortion issues. Future research should aim to develop more sophisticated methods for image modification.

Limited participation in the MR environment: Although the system is designed to support multiple participants, its current operation with only two participants highlights the need for network optimization and data compression as more people share the environment. Future efforts should aim to optimize data transmission to accommodate more users, extend local sharing to remote sharing, enhance the collaborative capabilities of the system, and integrate a wider range of interactive gestures for a more intuitive user experience.

Limitations in system integration: The system proposed in this dissertation is divided into three phases corresponding to chapters 3,4,5. different new features are added in each phase, which finally make up a completed system. However, due to the limitation of device performance and insufficient optimization, trying to open all the functions at the same time will cause the system to lag and affect the usage experience. Therefore, future optimization of system resource allocation is necessary.

References

- Albatayneh, A., Alterman, D., Page, A., & Moghtaderi, B. (2017). Discrepancies in peak temperature times using prolonged CFD simulations of housing thermal performance. *Energy Procedia*, 115, 253-264.
<https://doi.org/10.1016/j.egypro.2017.05.023>
- Alizadehsalehi, S., Hadavi, A., & Huang, J. C. (2020). From BIM to extended reality in AEC industry. *Automation in Construction*, 116, 103254.
<https://doi.org/10.1016/j.autcon.2020.103254>
- Andreini, P., Bonechi, S., Bianchini, M., Mecocci, A., & Scarselli, F. (2020). Image generation by GAN and style transfer for agar plate image segmentation. *Computer methods and programs in biomedicine*, 184, 105268.
<https://doi.org/10.1016/j.cmpb.2019.105268>
- Bay, E., Martinez-Molina, A., & Dupont, W. A. (2022). Assessment of natural ventilation strategies in historical buildings in a hot and humid climate using energy and CFD simulations. *Journal of Building Engineering*, 51, 104287.
<https://doi.org/10.1016/j.jobe.2022.104287>
- Berger, M., & Cristie, V. (2015). CFD post-processing in Unity3D. *Procedia Computer Science*, 51, 2913-2922. <https://doi.org/10.1016/B978-0-12-812372-0.00003-0>
- Boafo, F. E., Ahn, J. G., Kim, J. T., & Kim, J. H. (2015). Computing thermal bridge of VIP in building retrofits using DesignBuilder. *Energy Procedia*, 78, 400-405.
<https://doi.org/10.1016/j.egypro.2015.11.683>
- Bondakji, L. A., Lammich A. L., Werner L C. Vibe (virtual berlin)-immersive interactive 3d urban data visualization[C], 37th conference on education and research in computer aided architectural design in Europe (eCAADe) and 23rd SIGraDi architecture in the age of the 4th industrial revolution, Porto. 2019: 83-90. https://doi.org/10.5151/proceedings-ecaadesigradi2019_318
- Bournet, P. E., & Rojano, F. (2022). Advances of Computational Fluid Dynamics (CFD) applications in agricultural building modelling: Research, applications and challenges. *Computers and Electronics in Agriculture*, 201, 107277.
<https://doi.org/10.1016/j.compag.2022.107277>
- Buratti, C., Palladino, D., & Moretti, E. (2017). Prediction of indoor conditions and thermal comfort using CFD simulations: A case study based on experimental data. *Energy Procedia*, 126, 115-122.
<https://doi.org/10.1016/j.egypro.2017.08.130>
- Carbonari, A., Franco, C., Naticchia, B., Spegni, F., & Vaccarini, M. (2022). A Mixed Reality application for the on-site assessment of building renovation: development and testing. *Sustainability*, 14(20), 13239.
<https://doi.org/10.3390/su142013239>
- Cavigelli, L., Hager, P., & Benini, L. (2017, May). CAS-CNN: A deep convolutional neural network for image compression artifact suppression. In 2017

- International Joint Conference on Neural Networks (IJCNN) (pp. 752-759). IEEE. <https://doi.org/10.1109/IJCNN.2017.7965927>
- Chae, J., Kim, D., Jeong, W., Jo, E., Jeong, W. K., Choi, J., Kim, S., Kim, M. G. Lee, H. Han, J. (2022, November). Virtual air conditioner's airflow simulation and visualization in AR. In Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology (pp. 1-11). <https://doi.org/10.1145/3562939.3565615>
- Chai, C., Mustafa, K., Kuppasamy, S., Yusof, A., Lim, C. S., & Wai, S. H. (2019). BIM integration in augmented reality model. *Civ. Eng*, 10, 1266-1275. <https://doi.org/10.14716/ijtech.v10i7.3278>
- Chan, D. W., & Kumaraswamy, M. M. (1997). A comparative study of causes of time overruns in Hong Kong construction projects. *International Journal of project management*, 15(1), 55-63. [https://doi.org/10.1016/S0263-7863\(96\)00039-7](https://doi.org/10.1016/S0263-7863(96)00039-7)
- Chandler, T., Cordeil, M., Czauderna, T., Dwyer, T., Glowacki, J., Goncu, C., Stuerzlinger, W. & Wilson, E. (2015, September). Immersive analytics. In 2015 Big Data Visual Analytics (BDVA) (pp. 1-8). IEEE. <https://doi.org/10.1109/BDVA.2015.7314296>
- Cheng, J. C., & Ma, L. Y. (2013). A BIM-based system for demolition and renovation waste estimation and planning. *Waste management*, 33(6), 1539-1551. <https://doi.org/10.1016/j.wasman.2013.01.001>
- Cheng, Y. F., Yin, H., Yan, Y., Gugenheimer, J., & Lindlbauer, D. (2022, April). Towards understanding Diminished Reality. In Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (pp. 1-16). <https://doi.org/10.1145/3491102.3517452>
- Chronis, A., Dubor, A., Cabay, E., & Roudsari, M. S. (2017). Integration of CFD in computational design. *Proceedings of eCAADe 2017*, 601-610. <https://doi.org/10.52842/conf.ecaade.2017.1.601>
- Chung, T. J. (2002). *Computational Fluid Dynamics*. Cambridge university press. <https://doi.org/10.1017/cbo9780511606205>
- Cosco, F. I., Garre, C., Bruno, F., Muzzupappa, M., & Otaduy, M. A. (2009, October). Augmented touch without visual obtrusion. In 2009 8th IEEE International Symposium on Mixed and Augmented Reality (pp. 99-102). IEEE. <https://doi.org/10.1109/ISMAR.2009.5336492>
- Daemei, A. B., Limaki, A. K., & Safari, H. (2016). Opening performance simulation in natural ventilation using design builder (case study: a residential home in Rasht). *Energy Procedia*, 100, 412-422. <https://doi.org/10.1016/j.egypro.2016.10.196>
- Deininger, M. E., von der Grün, M., Piepereit, R., Schneider, S., Santhanavanich, T., Coors, V., & Voß, U. (2020). A continuous, semi-automated workflow: from 3D city models with geometric optimization and CFD simulations to visualization of wind in an urban environment. *ISPRS International Journal of Geo-Information*, 9(11), 657. <https://doi.org/10.3390/ijgi9110657>

- Dembski, F., Wössner, U., & Letzgus, M. (2019, September). The Digital Twin tackling urban challenges with models, spatial analysis and numerical simulations in immersive virtual environments. In Proceedings of the 37 eCAADe and XXIII SIGraDi Joint Conference: "Architecture in the Age of the 4th Industrial Revolution", Porto, Portugal (pp. 11-13).
https://doi.org/10.5151/proceedings-ecaadesigradi2019_334
- Den Hartog, J. P., Koutamanis, A., & Luscure, P. G. (2000). Possibilities and limitations of CFD simulation for indoor climate analysis. Fifth Design and Decision Support Systems in Architecture and Urban Planning-Part one: Architecture Proceedings, 152-167. <https://doi.org/10.3390/en10010139>
- Eastman, C. M. (2011). BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors. John Wiley & Sons.
<https://doi.org/10.5130/AJCEB.v12i3.2749>
- Enomoto, A., & Saito, H. (2007, November). Diminished Reality using multiple handheld cameras. In Proc. ACCV (Vol. 7, pp. 130-135).
<https://doi.org/10.1109/ICDSC.2007.4357531>
- Eskandari, R., & Motamedi, A. (2021). Diminished Reality in architectural and environmental design: Literature review of techniques, applications, and challenges. In ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction (Vol. 38, pp. 995-1001). IAARC Publications. <https://doi.org/10.22260/ISARC2021/0134>
- Fakra, A. H., Miranville, F., Boyer, H., & Guichard, S. (2011). Development of a new model to predict indoor daylighting: Integration in CODYRUN software and validation. Energy Conversion and Management, 52(7), 2724-2734.
<https://doi.org/10.1016/j.enconman.2011.01.019>
- Feng, H., Liyanage, D. R., Karunathilake, H., Sadiq, R., & Hewage, K. (2020). BIM-based life cycle environmental performance assessment of single-family houses: Renovation and reconstruction strategies for aging building stock in British Columbia. Journal of Cleaner Production, 250, 119543.
<https://doi.org/10.1016/j.jclepro.2019.119543>
- Fiorentino, M., Uva, A. E., Gattullo, M., Debernardis, S., & Monno, G. (2014). Augmented reality on large screen for interactive maintenance instructions. Computers in Industry, 65(2), 270-278.
<https://doi.org/10.1016/j.compind.2013.11.004>
- Franchi, V., & Ntagiou, E. (2021, November). Augmentation of a Virtual Reality environment using Generative Adversarial Networks. In 2021 IEEE international conference on artificial intelligence and Virtual Reality (AIVR) (pp. 219-223). IEEE. <https://doi.org/10.1109/AIVR52153.2021.00050>
- Fufa, S. M., Flyen, C., & Flyen, A. C. (2021). How can existing buildings with historic values contribute to achieving emission reduction ambitions?. Applied Sciences, 11(13), 5978. <https://doi.org/10.3390/app11135978>

- Fukuda, T., Mori, K., & Imaizumi, J. (2015). Integration of CFD, VR, AR and BIM for Design Feedback in a Design Process. *Educ. Res. Comput. Aided Archit. Des. Eur*, 1, 665-672. <https://doi.org/10.52842/conf.ecaade.2015.1.665>
- Fukuda, T., Yokoi, K., Yabuki, N., & Motamedi, A. (2019). An indoor thermal environment design system for renovation using augmented reality. *Journal of Computational Design and Engineering*, 6(2), 179-188. <https://doi.org/10.1016/j.jcde.2018.05.007>
- Fukuda, T., Zhu, Y., & Yabuki, N. (2018). Point Cloud Stream on Spatial Mixed Reality-Toward Telepresence in Architectural Field. In *Computing for a Better Tomorrow-Proceedings of the 36th eCAADe Conference (Vol. 2, pp. 727-734)*. <https://doi.org/10.52842/conf.ecaade.2018.2.727>
- Gauglitz, S., Nuernberger, B., Turk, M., & Höllerer, T. (2014, October). World-stabilized annotations and virtual scene navigation for remote collaboration. In *Proceedings of the 27th annual ACM symposium on User interface software and technology (pp. 449-459)*. <https://doi.org/10.1145/2642918.2647372>
- Ghassemi, R., & Becerik-Gerber, B. (2011). Transitioning to integrated project delivery: Potential barriers and lessons learned. *Lean construction journal*. <https://doi.org/10.1201/9781315185774-27>
- Giełżecki, J., & Jakubowski, T. (2018). The simulation of temperature distribution in a ground heat exchanger—GHE using the autodesk CFD simulation program. In *Renewable Energy Sources: Engineering, Technology, Innovation: ICORES 2017 (pp. 333-343)*. Springer International Publishing. https://doi.org/10.1007/978-3-319-72371-6_32
- Goldsmith, D., Liarokapis, F., Malone, G., & Kemp, J. (2008, July). Augmented reality environmental monitoring using wireless sensor networks. In *2008 12th International Conference Information Visualisation (pp. 539-544)*. IEEE. <https://doi.org/10.1109/IV.2008.72>
- Goodfellow, I., Pouget-Abadie, J., Mirza, M., Xu, B., Warde-Farley, D., Ozair, S., Courville, A. & Bengio, Y. (2014). Generative adversarial nets. *Advances in neural information processing systems*, 27. <https://doi.org/10.1145/3308558.3313564>
- Häkkinen, T., Ruuska, A., Vares, S., Pulakka, S., Kouhia, I., & Holopainen, R. (2012). Methods and concepts for sustainable renovation of buildings. VTT Technical Research Centre of Finland: Espoo, Finland, 154-196. <https://publications.vtt.fi/pdf/technology/2012/T26.pdf>
- Herling, J., & Broll, W. (2010, October). Advanced self-contained object removal for realizing real time Diminished Reality in unconstrained environments. In *2010 IEEE International Symposium on Mixed and Augmented Reality (pp. 207-212)*. IEEE. <https://doi.org/10.1109/ISMAR.2010.5643572>
- Herling, J., & Broll, W. (2012, November). Pixmix: A real time approach to high-quality Diminished Reality. In *2012 IEEE international symposium on mixed*

- and augmented reality (ISMAR) (pp. 141-150). IEEE.
<https://doi.org/10.1109/ISMAR.2012.6402551>
- Herling, J., & Broll, W. (2014). High-quality real time video inpainting with PixMix. *IEEE Transactions on Visualization and Computer Graphics*, 20(6), 866-879.
[https://doi.org/10.1016/0141-9331\(90\)90136-J](https://doi.org/10.1016/0141-9331(90)90136-J)
- Heuveline, V., Ritterbusch, S., & Ronnas, S. (2011). Augmented reality for urban simulation visualization. *Preprint Series of the Engineering Mathematics and Computing Lab*, (16). <https://doi.org/10.5772/7134>
- Horé, A., & Ziou, D. (2013). Is there a relationship between peak - signal - to - noise ratio and structural similarity index measure?. *IET Image Processing*, 7(1), 12-24. <https://doi.org/10.1049/iet-ipr.2012.0489>
- Hosokawa, M., Fukuda, T., Yabuki, N., Michikawa, T. and Motamedi, A. (2016, March). Integrating CFD and VR for indoor thermal design feedback. In *Proceedings of the 21st International Conference of the Association for Computer-Aided Architectural Design Research in Asia, CAADRIA* (pp. 477-486). <https://doi.org/10.52842/conf.caadria.2016.663>
- Hurnik, M., Specjal, A., Popiolek, Z., & Kierat, W. (2018). Assessment of single-family house thermal renovation based on comprehensive on-site diagnostics. *Energy and Buildings*, 158, 162-171.
<https://doi.org/10.1016/j.enbuild.2017.09.069>
- Huynh-Thu, Q., & Ghanbari, M. (2008). Scope of validity of PSNR in image/video quality assessment. *Electronics letters*, 44(13), 800-801.
<https://doi.org/10.1049/el:20080522>
- Inoue, K., Fukuda, T., Cao, R., & Yabuki, N. (2018). Tracking Robustness and Green View Index Estimation of Augmented and Diminished Reality for Environmental Design. *Proceedings of CAADRIA 2018*, 339-348.
<https://doi.org/10.52842/conf.caadria.2018.1.339>
- Isola, P., Zhu, J. Y., Zhou, T., & Efros, A. A. (2017). Image-to-image translation with conditional adversarial networks. In *Proceedings of the IEEE conference on computer vision and pattern recognition* (pp. 1125-1134).
<https://doi.org/10.1109/SENSORS43011.2019.8956702>
- Japan Meteorological Agency. (2023, October 31). Annual Solar Report. Retrieved from <http://www.data.jma.go.jp>
- Jensen, P. A., Thuvander, L., Femenias, P., & Visscher, H. (2022). Sustainable building renovation—strategies and processes. *Construction Management and Economics*, 40(3), 157-160. <https://doi.org/10.1080/01446193.2022.2045717>
- Jin, M., Zuo, W., & Chen, Q. (2012). Improvements of fast fluid dynamics for simulating air flow in buildings. *Numerical Heat Transfer, Part B: Fundamentals*, 62(6), 419-438. <https://doi.org/10.1080/10407790.2012.724988>
- Jing, J., Deng, X., Xu, M., Wang, J., & Guan, Z. (2021). HiNet: deep image hiding by invertible network. In *Proceedings of the IEEE/CVF international conference*

- on computer vision (pp. 4733-4742).
<https://doi.org/10.1109/ICCV48922.2021.00469>
- Jonson, B. (2005). Design ideation: the conceptual sketch in the digital age. *Design studies*, 26(6), 613-624. <https://doi.org/10.1016/j.destud.2005.03.001>
- Kan, P., Kurtic, A., Radwan, M., & Rodriguez, J. M. L. (2021). Automatic interior Design in Augmented Reality Based on hierarchical tree of procedural rules. *Electronics*, 10(3), 245. <https://doi.org/10.3390/electronics10030245>
- Katsuno, J., Bahadur, R. H., & Kikuchi, S. (2011). Investigation of the thermal comfort and overall comfort in the living room. *Nihon Kentikugakkaitaikai Gakuziyutukōen Kōgaisyū (Summaries of Technical Papers of Annual Meeting AIJ)*, D-2, pp. 385-386.
- Kawai, N., Sato, T., & Yokoya, N. (2013, October). Diminished Reality considering background structures. In *2013 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (pp. 259-260). IEEE.
<https://doi.org/10.1109/ISMAR.2013.6671794>
- Kawai, N., Sato, T., & Yokoya, N. (2014). From image inpainting to Diminished Reality. In *Virtual, Augmented and Mixed Reality. Designing and Developing Virtual and Augmented Environments: 6th International Conference, VAMR 2014, Held as Part of HCI International 2014, Heraklion, Crete, Greece, June 22-27, 2014, Proceedings, Part I 6* (pp. 363-374). Springer International Publishing. https://doi.org/10.1007/978-3-319-07458-0_34
- Kawai, N., Sato, T., & Yokoya, N. (2015). Diminished Reality based on image inpainting considering background geometry. *IEEE transactions on visualization and computer graphics*, 22(3), 1236-1247.
<https://doi.org/10.1109/TVCG.2015.2462368>
- Kido, D., Fukuda, T., & Yabuki, N. (2020). Diminished Reality system with real time object detection using deep learning for onsite landscape simulation during redevelopment. *Environmental Modelling & Software*, 131, 104759.
<https://doi.org/10.1016/j.envsoft.2020.104759>
- Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., Behar, V. J., Hern, S. C., Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *Journal of Exposure Science & Environmental Epidemiology*, 11(3), 231-252. <https://doi.org/10.1038/sj.jea.7500165>
- Kovacic, I., Summer, M., & Achammer, C. (2015). Strategies of building stock renovation for ageing society. *Journal of cleaner production*, 88, 349-357.
<https://doi.org/10.1016/j.jclepro.2014.04.080>
- Kubota, T., Chyee, D. T. H., & Ahmad, S. (2009). The effects of night ventilation technique on indoor thermal environment for residential buildings in hot-humid climate of Malaysia. *Energy and buildings*, 41(8), 829-839.
<https://doi.org/10.1016/j.enbuild.2009.03.008>

- Kunert, C., Schwandt, T., & Broll, W. (2019, October). An efficient Diminished Reality approach using real time surface reconstruction. In 2019 International Conference on Cyberworlds (CW) (pp. 9-16). IEEE.
<https://doi.org/10.1109/CW.2019.00010>
- Lai, H., Deng, X., & Chang, T. Y. P. (2019). BIM-based platform for collaborative building design and project management. *Journal of Computing in Civil Engineering*, 33(3), 05019001. [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.0000830](https://doi.org/10.1061/(ASCE)CP.1943-5487.0000830)
- Laplane, P. A., & Neill, C. J. (2004). The Demise of the Waterfall Model Is Imminent, and Other Urban Myths: Rumors of the demise of the Waterfall Life-cycle Model are greatly exaggerated. *Queue*, 1(10), 10-15.
<https://doi.org/10.1145/971564.971573>
- Lee, J., Miri, M., & Newberry, M. (2023). Immersive Virtual Reality, Tool for Accessible Design: Perceived Usability in an Interior Design Studio Setting. *Journal of Interior Design*, 10717641231182981.
<https://doi.org/10.1111/joid.12171>
- Lee, M., Park, G., Jang, H., & Kim, C. (2021). Development of building cfd model design process based on BIM. *Applied Sciences*, 11(3), 1252.
<https://doi.org/10.3390/app11031252>
- Lei, Z., Liu, C., Wang, L., & Li, N. (2017). Effect of natural ventilation on indoor air quality and thermal comfort in dormitory during winter. *Building and Environment*, 125, 240-247. <https://doi.org/10.1016/j.buildenv.2017.08.051>
- LI, Q., Takeuchi, O., Shishido, H., Kameda, Y., Kim, H., & Kitahara, I. (2022). Generative image quality improvement in omnidirectional free-viewpoint images and assessments. *IEEE Transactions on Image Electronics and Visual Computing*, 10(1), 107-119. <https://doi.org/10.5220/0008959802990306>
- Li, Z., Wang, Y., Guo, J., Cheong, L. F., & Zhou, S. Z. (2013, October). Diminished Reality using appearance and 3D geometry of internet photo collections. In 2013 IEEE International Symposium on Mixed and Augmented Reality (ISMAR) (pp. 11-19). IEEE. <https://doi.org/10.1109/ISMAR.2013.6671759>
- Li, Z., Xia, B., Zhang, J., Wang, C., & Li, B. (2022). A comprehensive survey on data-efficient GANs in image generation. *arXiv preprint arXiv:2204.08329*.
<https://doi.org/10.48550/arXiv.2204.08329>
- Lin, C. H., Chang, C. C., Chen, Y. S., Juan, D. C., Wei, W., & Chen, H. T. (2019). Coco-gan: Generation by parts via conditional coordinating. In *Proceedings of the IEEE/CVF international conference on computer vision* (pp. 4512-4521).
<https://doi.org/10.1109/ICCV.2019.00461>
- Liu, M. Y., Huang, X., Yu, J., Wang, T. C., & Mallya, A. (2021). Generative adversarial networks for image and video synthesis: Algorithms and applications. *Proceedings of the IEEE*, 109(5), 839-862.
<https://doi.org/10.1109/JPROC.2021.3049196>

- Liu, X., Xie, N., & Jia, J. (2015, October). WebVis_BIM: Real time web3D visualization of big BIM data. In Proceedings of the 14th ACM SIGGRAPH International Conference on Virtual Reality Continuum and its Applications in Industry (pp. 43-50). <https://doi.org/10.1145/2817675.2817678>
- Liu, Y., Van Nederveen, S., & Hertogh, M. (2017). Understanding effects of BIM on collaborative design and construction: An empirical study in China. *International journal of project management*, 35(4), 686-698. <https://doi.org/10.1016/j.ijproman.2016.06.007>
- Loli, A., & Bertolin, C. (2018). Towards zero-emission refurbishment of historic buildings: A literature review. *Buildings*, 8(2), 22. <https://doi.org/10.3390/buildings8020022>
- Ludwig, M., Berrier, S., Tetzlaff, M., & Meyer, G. (2015). 3D shape and texture morphing using 2D projection and reconstruction. *Computers & Graphics*, 51, 146-156. <https://doi.org/10.1016/j.cag.2015.05.005>
- Malkawi, A. M., & Srinivasan, R. S. (2005). A new paradigm for Human-Building Interaction: the use of CFD and Augmented Reality. *Automation in construction*, 14(1), 71-84. <https://doi.org/10.1016/j.autcon.2004.08.001>
- Matsuo, J., Murayama, T., & Tochiara, Y. (2006). Effects of different vertical air temperatures on thermal comfort and mental performance. *Japanese journal of biometeorology*, 43(2), 79-89. <https://doi.org/10.1080/15298668791385093>
- Meerits, S., & Saito, H. (2015, August). Visualization of dynamic hidden areas by real time 3d structure acquisition using rgb-d camera. In 3D Systems and Applications Conference. <https://doi.org/10.1109/TVCG.2019.2930691>
- Meerits, S., & Saito, H. (2015, September). Real time Diminished Reality for dynamic scenes. In 2015 IEEE International Symposium on Mixed and Augmented Reality Workshops (pp. 53-59). IEEE. <https://doi.org/10.1109/ISMARW.2015.19>
- Meerits, S., Nozick, V., & Saito, H. (2019). Real time scene reconstruction and triangle mesh generation using multiple RGB-D cameras. *Journal of Real time Image Processing*, 16, 2247-2259. <https://doi.org/10.1007/s11554-017-0736-x>
- Mertayasa, I. K., Rahardja, U., Hardini, M., & Harahap, E. P. (2023). Interior Design Alphabet Incubator 3.0 Based on Planner 5D. *Technomedia Journal*, 8(1 Juni), 82-108.
- Microsoft. (2023, October 31). Microsoft-HoloLens. Retrieved from <https://www.microsoft.com/en-us/hololens>
- Milgram, P., & Kishino, F. (1994). A taxonomy of Mixed Reality visual displays. *IEICE Transactions on Information and Systems*, 77(12), 1321-1329. [https://doi.org/10.1016/0141-9382\(83\)90256-1](https://doi.org/10.1016/0141-9382(83)90256-1)
- Mori, S., Erat, O., Broll, W., Saito, H., Schmalstieg, D., & Kalkofen, D. (2020). InpaintFusion: incremental RGB-D inpainting for 3D scenes. *IEEE Transactions on Visualization and Computer Graphics*, 26(10), 2994-3007. <https://doi.org/10.1109/TVCG.2020.3003768>

- Mori, S., Ikeda, S., & Saito, H. (2017). A survey of Diminished Reality: Techniques for visually concealing, eliminating, and seeing through real objects. *IPSJ Transactions on Computer Vision and Applications*, 9(1), 1-14.
<https://doi.org/10.3390/electronics10080900>
- Mori, S., Shibata, F., Kimura, A., & Tamura, H. (2015, September). Efficient use of textured 3D model for pre-observation-based Diminished Reality. In 2015 IEEE international symposium on mixed and augmented Reality workshops (pp. 32-39). IEEE. <https://doi.org/10.1109/ISMARW.2015.16>
- Nakajima, Y., Mori, S., & Saito, H. (2017, October). Semantic object selection and detection for Diminished Reality based on slam with viewpoint class. In 2017 IEEE International Symposium on Mixed and Augmented Reality (ISMAR-Adjunct) (pp. 338-343). IEEE. <https://doi.org/10.1109/ISMAR-Adjunct.2017.98> <http://10.1109/ISMAR-Adjunct.2017.98>
- Nishihara, A., & Okamoto, J. (2015, November). Object recognition in assembly assisted by augmented reality system. In 2015 SAI Intelligent Systems Conference (IntelliSys) (pp. 400-407). IEEE.
<http://10.1109/IntelliSys.2015.7361172>
- Novak, J. I., & Loy, J. (2018). Digital technologies and 4D customized design: challenging conventions with responsive design. In *Handbook of research on human development in the digital age* (pp. 403-426). IGI Global.
<http://10.4018/978-1-5225-9624-0.ch001>
- Nozaki, F. (2018). *Numerical Analysis of Heat Transfer and Flow by OpenFOAM*. Open CAE Society (Ed.). Tokyo: Morikita Publishing.
- Oh, M., Lee, J., Hong, S. W., & Jeong, Y. (2015). Integrated system for BIM-based collaborative design. *Automation in construction*, 58, 196-206.
<http://10.1016/j.autcon.2015.07.015>
- Ohno, N., & Kageyama, A. (2007). Scientific visualization of geophysical simulation data by the CAVE VR system with volume rendering. *Physics of the Earth and Planetary Interiors*, 163(1-4), 305-311.
<https://doi.org/10.1016/j.pepi.2007.02.013>
- OpenFOAM. (2023, October 31). OpenFOAM Release History. Retrieved from <https://www.openfoam.com>
- Ozdemir, M. A. (2021). Virtual Reality (VR) and augmented reality (AR) technologies for accessibility and marketing in the tourism industry. In *ICT tools and applications for accessible tourism* (pp. 277-301). IGI Global.
<https://doi.org/10.4018/978-1-7998-6428-8.ch013>
- Paes, D., & Irizarry, J. (2018). A usability study of an immersive Virtual Reality platform for building design review: Considerations on human factors and user interface. In *Construction Research Congress 2018* (pp. 419-428).
<http://10.1061/9780784481264.041>

- Panchal, H. N., & Shah, P. K. (2013). Modeling and verification of hemispherical solar still using ANSYS CFD. *International Journal of Energy and Environment (Print)*, 4. <http://10.1016/j.desal.2011.11.047>
- Paul, B. (2023, October 31). Converting to/from cubemaps. Retrieved from <https://paulbourke.net/panorama/cubemaps>
- Paule, B., Flourentzou, F., Pantet, S., Boutillier, J., Heeren, N., & Voellinger, A. B. T. (2012, September). DIAL+ Suite: a new suite of tools to optimize the global energy performance of room design. In *Status Seminar, Zurich (Vol. 12)*. [http://10.1016/0038-092X\(77\)90053-6](http://10.1016/0038-092X(77)90053-6)
- Paule, B., Sok, E., Pantet, S., & Boutillier, J. (2017). Electrochromic glazings: dynamic simulation of both daylight and thermal performance. *Energy Procedia*, 122, 199-204. <http://10.1016/j.egypro.2017.07.345>
- Pointwise. (2023, October 31). Pointwise Official Website. Retrieved from <http://www.pointwise.com>
- Poly Haven. (2023, October 31). HDRIs: Indoor. Retrieved from HDRIHaven. <https://polyhaven.com/hdris/indoor>.
- Prabhakaran, A., Mahamadu, A. M., Mahdjoubi, L., & Manu, P. (2020). An approach for integrating Mixed Reality into BIM for early stage design coordination. In *MATEC Web of Conferences (Vol. 312, p. 04001)*. EDP Sciences. <https://doi.org/10.1051/mateconf/202031204001>
- Radford, A., Metz, L., & Chintala, S. (2015). Unsupervised representation learning with deep convolutional Generative Adversarial Networks. <https://doi.org/10.23919/ChiCC.2018.8482813>
- Remeikienė, R., Gasparėnienė, L., Fedajev, A., Szarucki, M., Đekić, M., & Razumienė, J. (2021). Evaluation of sustainable energy development progress in EU member states in the context of building renovation. *Energies*, 14(14), 4209. <https://doi.org/10.3390/en14144209>
- RICOH360. (2023, October 31). THETA developers' API. Retrieved from <https://github.com/ricohapi/theta-api-specs>
- Rohdin, P., Molin, A., & Moshfegh, B. (2014). Experiences from nine passive houses in Sweden—Indoor thermal environment and energy use. *Building and Environment*, 71, 176-185. <https://doi.org/10.1016/j.buildenv.2013.09.017>
- Sankar, A., & Seitz, S. M. (2017, October). Interactive room capture on 3d-aware mobile devices. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (pp. 415-426).
- Sasanuma, H., Manabe, Y., & Yata, N. (2016, September). Diminishing real objects and adding virtual objects using a RGB-D camera. In *2016 IEEE International Symposium on Mixed and Augmented Reality (ISMAR-Adjunct)* (pp. 117-120). IEEE. <https://doi.org/10.1109/ISMAR-Adjunct.2016.0055>
- Savioja, L., Mantere, M., Olli, I., Äyräväinen, S., Gröhn, M., & Iso-Aho, J. (2003). Utilizing virtual environments in construction projects. *Journal of Information*

- Technology in Construction (ITcon), 8(7), 85-99.
<https://doi.org/10.4324/9780203475782-30>
- Shimabara, B., & Hirano, M. (2014) Challenges and growth potential of the Japanese housing market & Existing housing-related housing policy trends. In Stock & Renovation 2014; Wada, Y. (Ed.). Tokyo: HOME'S Research Institute.
- Shutterstock. (2023, October 31). Royalty-free images of Indoor panorama. Retrieved from <https://www.shutterstock.com/ja/search/indoor-panorama>
- Siltanen, S. (2017). Diminished Reality for augmented reality interior design. *The Visual Computer*, 33, 193-208. <https://doi.org/10.1007/s00371-015-1174-z>
- Slater, M., & Sanchez-Vives, M. V. (2016). Enhancing our lives with immersive Virtual Reality. *Frontiers in Robotics and AI*, 3, 74.
<https://doi.org/10.3389/frobt.2016.00074>
- Solmaz, S., & Van Gerven, T. (2022). Automated integration of extract-based CFD results with AR/VR in engineering education for practitioners. *Multimedia Tools and Applications*, 81(11), 14869-14891. <https://doi.org/10.1007/s11042-021-10621-9>
- Speicher, M., Hall, B. D., & Nebeling, M. (2019, May). What is Mixed Reality?. In *Proceedings of the 2019 CHI conference on human factors in computing systems* (pp. 1-15). <https://doi.org/10.2307/j.ctv173dzn6.8>
- Steuer, J., Biocca, F., & Levy, M. R. (1995). Defining Virtual Reality: Dimensions determining telepresence. *Communication in the age of Virtual Reality*, 33, 37-39. <https://doi.org/10.1111/j.1460-2466.1992.tb00812.x>
- Sun, J., Mi, S., Olsson, P. O., Paulsson, J., & Harrie, L. (2019). Utilizing BIM and GIS for Representation and Visualization of 3D Cadastre. *ISPRS International journal of geo-information*, 8(11), 503. <https://doi.org/10.3390/ijgi8110503>
- Tanabe, S. I., Iwahashi, Y., Tsushima, S., & Nishihara, N. (2013). Thermal comfort and productivity in offices under mandatory electricity savings after the Great East Japan earthquake. *Architectural Science Review*, 56(1), 4-13.
<https://doi.org/10.1080/00038628.2012.744296>
- Tang, H., Bai, S., Torr, P. H., & Sebe, N. (2020a). Bipartite graph reasoning gans for person image generation. *arXiv preprint arXiv:2008.04381*.
<https://doi.org/10.48550/arXiv.2008.04381>
- Tang, H., Bai, S., Zhang, L., Torr, P. H., & Sebe, N. (2020b). Xinggan for person image generation. In *Computer Vision—ECCV 2020: 16th European Conference, Glasgow, UK, August 23–28, 2020, Proceedings, Part XXV 16* (pp. 717-734). Springer International Publishing. https://doi.org/10.1007/978-3-030-58595-2_43
- Teo, T., Lawrence, L., Lee, G. A., Billingham, M., & Adcock, M. (2019, May). Mixed Reality remote collaboration combining 360 video and 3d reconstruction. In *Proceedings of the 2019 CHI conference on human factors in computing systems* (pp. 1-14). <https://doi.org/10.1145/3290605.3300431>

- Thermoclon. (2023, October 31). Temperature data logger Thermoclon G type. Retrieved from <http://www.kn-labs.com/thermochron.htm>
- Unity. (2023, October 31). 2020. Unity documentation. Retrieved from <https://docs.unity3d.com/Manual/UNet.html>
- Wang, P., Wang, Y., Billingham, M., Yang, H., Xu, P., & Li, Y. (2023). BeHere: a VR/SAR remote collaboration system based on virtual replicas sharing gesture and avatar in a procedural task. *Virtual Reality*, 1-22. <https://doi.org/10.1145/3089269.3089281>
- Wang, X., Love, P. E., Kim, M. J., Park, C. S., Sing, C. P., & Hou, L. (2013). A conceptual framework for integrating building information modeling with augmented reality. *Automation in construction*, 34, 37-44. <https://doi.org/10.1016/j.autcon.2012.10.012>
- Wang, Z., Bovik, A. C., Sheikh, H. R., & Simoncelli, E. P. (2004). Image quality assessment: from error visibility to structural similarity. *IEEE transactions on image processing*, 13(4), 600-612. <https://doi.org/10.1109/TIP.2003.819861>
- Watson, A. (2011). Digital buildings—Challenges and opportunities. *Advanced engineering informatics*, 25(4), 573-581. <https://doi.org/10.1016/j.aei.2011.07.003>
- Werrlich, S., Daniel, A., Ginger, A., Nguyen, P. A., & Notni, G. (2018, October). Comparing HMD-based and paper-based training. In 2018 IEEE International Symposium on Mixed and Augmented Reality (ISMAR) (pp. 134-142). IEEE. <https://doi.org/10.21428/70cb44c5.29cb2179>
- Woksepp, S., & Olofsson, T. (2008). Credibility and applicability of Virtual Reality models in design and construction. *Advanced Engineering Informatics*, 22(4), 520-528. <https://doi.org/10.1016/j.aei.2008.06.007>
- Yabuki, N., Furubayashi, S., Hamada, Y., & Fukuda, T. (2012). Collaborative visualization of environmental simulation result and sensing data using augmented reality. In *Cooperative Design, Visualization, and Engineering: 9th International Conference, CDVE 2012, Osaka, Japan, September 2-5, 2012. Proceedings 9* (pp. 227-230). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-32609-7_32
- Yan, D., Xia, J., Tang, W., Song, F., Zhang, X., & Jiang, Y. (2008, June). DeST—An integrated building simulation toolkit Part I: Fundamentals. In *Building Simulation* (Vol. 1, pp. 95-110). Tsinghua Press. <https://doi.org/10.1007/s12273-008-8118-8>
- Yan, J., Kensek, K., Konis, K., & Noble, D. (2020). Cfd visualization in a Virtual Reality environment using building information modeling tools. *Buildings*, 10(12), 229. <https://doi.org/10.3390/buildings10120229>
- Yang, C., Shen, Y., & Zhou, B. (2021). Semantic hierarchy emerges in deep generative representations for scene synthesis. *International Journal of Computer Vision*, 129, 1451-1466. <https://doi.org/10.1007/s11263-020-01429-5>

- Yao, J., & Zhu, N. (2012). Evaluation of indoor thermal environmental, energy and daylighting performance of thermotropic windows. *Building and Environment*, 49, 283-290. <https://doi.org/10.1016/j.buildenv.2011.06.004>
- Yoon, Y., Moon, J. W., & Kim, S. (2016). Development of annual daylight simulation algorithms for prediction of indoor daylight illuminance. *Energy and Buildings*, 118, 1-17. <https://doi.org/10.1016/j.enbuild.2016.02.030>
- Yun, K., Lu, T., & Chow, E. (2018, April). Occluded object reconstruction for first responders with augmented reality glasses using conditional Generative Adversarial Networks. In *Pattern Recognition and Tracking XXIX* (Vol. 10649, pp. 225-231). SPIE. <https://doi.org/10.1117/12.2305151>
- Zhang, B., Gu, S., Zhang, B., Bao, J., Chen, D., Wen, F., Wang, Y., Guo, B. (2022). Styleswin: Transformer-based gan for high-resolution image generation. In *Proceedings of the IEEE/CVF conference on computer vision and pattern recognition* (pp. 11304-11314). <https://doi.org/10.2139/ssrn.4280052>
- Zhu, J., Shen, Y., Zhao, D., & Zhou, B. (2020, August). In-domain gan inversion for real image editing. In *European conference on computer vision* (pp. 592-608). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-58520-4_35
- Zhu, Y., Fukuda, T., & Yabuki, N. (2018, May). Slam-based MR with animated CFD for building design simulation. In *Proceedings of the 23rd International Conference of the Association for Computed-Aided Architectural Design Research in Asia (CAADRIA)*, Tsinghua University, School of Architecture, Beijing, China (pp. 17-19). <https://doi.org/10.52842/conf.caadria.2018.1.391>
- Zhu, Y., Fukuda, T., & Yabuki, N. (2019, April). Synthesizing 360-degree live streaming for an erased background to study renovation using Mixed Reality. In *Proceedings of the 24th International Conference of the Association for Computed-Aided Architectural Design Research in Asia (CAADRIA)*, Victoria University of Wellington, Faculty of Architecture & Design (pp. 71-80). <https://doi.org/10.52842/conf.caadria.2019.2.071>
- Zhu, Y., Ouyang, Q., Cao, B., Zhou, X., & Yu, J. (2016). Dynamic thermal environment and thermal comfort. *Indoor air*, 26(1), 125-137. <https://doi.org/10.1111/ina.12233>