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**SPATIAL AUGMENTED REALITY FOR
3-DIMENSIONAL (3D) ARCHITECTURAL DESIGN
VISUALIZATION AND COLLABORATION**

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PhD

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The Department of Building and Real Estate

Spatial Augmented Reality for
3-Dimensional (3D) Architectural Design
Visualization and Collaboration

JIN Yixuan

A thesis submitted in partial fulfilment of the requirements for the
degree of Doctor of Philosophy

December 2024

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ABSTRACT

As building Information modelling (BIM) and augmented reality (AR) becomes more commonplace in collaborative design, a number of critical shortcomings have emerged—most noticeably in the areas of technical performance, user engagement, and overall visual quality. These challenges have, in turn, stimulated renewed curiosity in Spatial Augmented Reality (SAR) approaches. Unlike conventional mixed reality approaches, SAR technology projects digital content directly onto physical surfaces, achieving an unprecedented seamless integration of virtual and real environments with photorealistic quality. This advanced approach provides superior immersion, spatial cognition, and visualization fidelity compared to both immersive virtual reality systems and traditional augmented reality implementations.

Conventional AR systems primarily operate through direct 3D-to-3D alignment, where digital models are matched precisely with their physical counterparts. SAR, however, employs a more complex workflow - first converting 3D data into 2D projections that are then remapped into 3D space. This dimensional transformation presents significant technical hurdles in preserving both geometric precision and visual quality throughout the conversion process. The challenges become particularly pronounced when simulating daylight effects, where SAR systems must use stationary projectors to represent the sun's dynamic movement, which is a stark contrast to BIM environments that can directly simulate solar positions. These technical considerations are especially critical for architectural visualization, where accurately representing building exteriors and environmental impacts remains paramount for effective design collaboration. The research framework consequently focuses on addressing these fundamental challenges across both domains.

This research firstly presents an BIM-based projection mapping framework that utilizes SAR technology to enhance architectural design collaboration. The comprehensive framework details the complete procedural workflow and technical specifications for generating 3D models and applying textures to physical surfaces. Through rigorous testing with a projection mapping tool, we successfully demonstrated stable projection of virtual building models onto physical objects, effectively addressing key limitations of existing AR-based collaboration systems. Our experimental results reveal significant improvements from optimized control parameters, including enhanced model clarity at larger scales and superior stereoscopic projection in low-light conditions. However, persistent challenges with manual calibration for complex geometries and dynamic projection scenarios highlight the need for automated calibration solutions to fully unlock SAR's potential for cross-disciplinary collaboration.

To overcome these calibration challenges, we developed an automated geometric calibration system employing a projector-camera configuration. Our innovative solution utilizes machine vision algorithms operating with an uncalibrated projector-camera pair to establish precise spatial alignment. Extensive validation across diverse building models and hardware setups confirmed the system's high accuracy. The solution offers multiple advantages, including the elimination of separate projector-camera calibration requirements, a streamlined single-phase calibration process, simplified user interaction requiring only white panel placement and image capture, and seamless integration with BIM model textures for enhanced design compatibility.

The research further extends to daylight simulation applications in architectural design, addressing the realism and collaboration limitations inherent in current mixed reality technologies. Our SAR-based daylight simulation system incorporates advanced solar position algorithms and a custom-developed plugin for the SPARK platform, generating high-fidelity

building textures, daylight beams, and shadow patterns with exceptional accuracy. Comparative studies demonstrate SAR's superior performance over software-based simulations across critical metrics, including visual authenticity, spatial presence, and user engagement. By enabling real-time feedback and immersive visualization capabilities, the system facilitates a more dynamic and interactive design process accessible to both professional practitioners and public stakeholders.

PUBLICATIONS ARISING FROM THE THESIS

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Spatial Augmented Reality (SAR)-based Daylight Simulation and Visualization for Building Exterior Design. (Journal paper pending submission in 2025)

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TABLE OF CONTENTS

ABSTRACT.....	I
PUBLICATIONS ARISING FROM THE THESIS.....	IV
ACKNOWLEDGEMENTS.....	V
TABLE OF CONTENTS.....	VI
LIST OF FIGURES	IX
LIST OF TABLES.....	XI
LIST OF ABBREVIATIONS.....	XII
Chapter 1 Introduction	1
1.1 Research Background	1
1.1.1 Collaborative Design	1
1.1.2 Architectural Design Collaboration	1
1.1.3 Visualization Technologies of Architectural Design.....	4
1.1.4 Daylight Simulation for Architectural Design.....	7
1.2 Research Problems	7
1.3 Research Objectives	9
Chapter 2 Literature Review	12
2.1 Augmented Reality	12
2.1.1 Overview.....	12
2.1.2 Technologies of AR	13
2.1.3 AR for BIM-Based Architectural Design Collaboration	16
2.2 Spatial Augmented Reality	18
2.2.1 Definition of SAR	18
2.2.2 Comparison Between AR and SAR.....	19
2.2.3 General Applications	21
2.2.4 Studies on SAR Applications in the Building Field	23
2.3 Geometric Calibration of SAR.....	25
2.3.1 Geometric Alignment.....	25
2.3.2 Geometric Distortion	25
2.4 Existing Geometric Calibration Methods	27
2.4.1 Sensor-based Technology	27
2.4.2 Vision-based Technology	28
2.4.3 Comparison of Geometric Calibration Methods.....	29
2.5 Advantages of SAR-based BIM Visualization for Architectural Design Review	31
Chapter 3 BIM-based SAR for Architectural Design Collaboration: A Proof of Concept	35
3.1 Background	35

3.2 Methodology	37
3.2.1 Creating 3D Models with UV Map and Texture Image	37
3.2.2 Implement Projection Mapping	39
3.3 Results and Discussion	40
3.3.1 Case Procedures of BIM-Based SAR	40
3.3.2 Control Group Design and Results	43
3.3.3 Discussion	46
3.4 Conclusion	49
Chapter 4 SAR-based 3D BIM Visualization through Automated Geometric Calibration of a Projector-Camera System	51
4.1 Background	51
4.2 Geometric Calibration for SAR	52
4.2.1 Some Current Automatic SAR Geometric Calibration Systems	54
4.2.2 Projector-camera Calibration	55
4.2.3 Limitations of Existing SAR Geometric Calibration Systems When Applying to the AEC Industry	56
4.3 Methodology	57
4.3.1 Marker Detection	59
4.3.2 Object-projector Correspondence Estimation	63
4.3.3 Three-point Perspective Projection Correction	65
4.3.4 Error Estimation	68
4.4 Results and Discussion	70
4.4.1 Projection Results	70
4.4.2 Error Estimation and Discussion	73
4.5 Conclusion	75
Chapter 5 Spatial Augmented Reality (SAR)-based Daylight Simulation and Visualization for Building Exterior Design	77
5.1 Background	77
5.2 Daylight Simulation	78
5.2.1 Building Information Modelling on Daylight Simulation	78
5.2.2 Mixed Reality Technology for Daylight Simulation	80
5.2.3 SAR for Daylight Simulation	82
5.3 Methodology	84
5.3.1 SAR Platform Selection for Daylight Simulation Plugin	86
5.3.2 Introduction of SPARK Platform	86
5.3.3 Daylight Simulation Algorithm and Plugin Development	90
5.4 Application Procedures	93
5.4.1 Prototype Preparation	93

5.4.2 System Calibration.....	94
5.4.3 Execution of Projection Mapping	95
5.5 User Survey for Evaluating SAR-based Daylight Simulation.....	100
5.5.1 Survey Design.....	100
5.5.2 Results and Discussion	103
5.6 Conclusion	109
Chapter 6 Conclusions and Future Research	111
6.1 Review of Research Background.....	111
6.2 Research Objectives and Major Findings	111
6.3 Contributions of the Study	113
6.4 Limitations and Future Research	114
6.5 Conclusions.....	115
References.....	116

LIST OF FIGURES

Figure 1-1 Research Framework.....	10
Figure 2-1 Reality-Virtuality Continuum	12
Figure 2-2 Principles of optical see-through display and video see-through display	14
Figure 2-3 A visual classification of popular video and optical see-through display headsets in the market.....	14
Figure 2-4 Smartphones, PDA and Tablet PC are used as the Handheld display of AR.....	15
Figure 2-5 AR on-site foresee of the constructed building.....	16
Figure 2-6 Auto AR system allows the user to experience virtual building models	17
Figure 2-7 Basic Concept of Spatial Augmented Reality	19
Figure 2-8 Various methods and the position of the display medium	20
Figure 2-9 Projective texture on a car model.....	22
Figure 2-10 Typical foam model of a car augmented by projection.....	22
Figure 2-11 The dashboard prototype is augmented with a leather interior	23
Figure 2-12 Oven design projection	23
Figure 2-13 Mock-up projection of a building wall.....	24
Figure 2-14 Physical model with the projection of the city model over the wooden structure	24
Figure 2-15 Projection augmented Cinderella's Castle at the Magic Kingdom Park.....	25
Figure 2-16 keystoning effect occurs due to the projection angle between the projector and the projection surface.....	26
Figure 2-17 Radial distortion	27
Figure 3-1 BIM-based SAR Implementation Framework for Building Design Prototyping. .	37
Figure 3-2 Case procedures	42
Figure 3-4 Comparison of projection results with illumination condition	44
Figure 3-5 Comparison of projection results in different projection angles.	45
Figure 3-6 Comparison of projection results on planar/curved surfaces with various building textures.....	46
Figure 4-1 System overview	57
Figure 4-2 System technical structure.....	59
Figure 4-3 Flowchart of Marker Detection	59
Figure 4-4 Flowchart of object-projector correspondence Estimation	63
Figure 4-5 Illustration of image projective transformation.....	64
Figure 4-6 Flowchart of three-point perspective projection correction	65
Figure 4-7 Perspective projection diagram	66
Figure 4-8 Brick texture image	68
Figure 4-9 Experiment settlement.....	70

Figure 4-10 Sample geometric calibration flowchart	71
Figure 4-11 Projection with designed BIM model texture	72
Figure 4-12 Model graphical representation for error estimation.....	73
Figure 4-13 Image projection on the reference planar	74
Figure 5-1 Flowchart of SAR-based Daylight Simulation System.....	84
Figure 5-2 System Equipment Setup	85
Figure 5-3 SPARK for Industrial Design.....	87
Figure 5-4 Using local homographies to estimate projected corner locations to each corner in the camera image	89
Figure 5-5 Comparison of daylight simulation between VR and SAR	90
Figure 5-6 Development of daylight simulation interface	93
Figure 5-7 building prototype with hemispherical reflective markers.....	94
Figure 5-8 Building 3D obj. file	95
Figure 5-9 Texture images	96
Figure 5-10 Architectural design interface	96
Figure 5-11 Daylight simulation interface with building model	97
Figure 5-12 Daylight simulation with building design 1	98
Figure 5-13 Daylight simulation with building design 2	99
Figure 5-14 Simulation of building design 2 with real-time adjustable window design.....	99
Figure 5-15 Video captures of SAR-based simulation and software-based simulation	103
Figure 5-16 Scoring ratio histogram of naturalness factor.	105
Figure 5-17 Scoring ratio histogram of spatial presence factor.	105
Figure 5-18 Scoring ratio histogram of engagement factor.	106

LIST OF TABLES

Table 1-1 Technological differences between AR and SAR	21
Table 2-1 Comparison of geometric calibration methods.....	30
Table 2-2 A summary of building model visualization techniques	32
Table 4-1 Information of Error Estimation	74
Table 5-1 Naturalness factor inventory.....	101
Table 5-2 Spatial presence factor inventory	102
Table 5-3 Engagement factor inventory	102
Table 5-4 Descriptive statistics of sense of presence survey	104
Table 5-5 Results of paired t test of SAR-based simulation and desktop-based simulation .	107

LIST OF ABBREVIATIONS

AEC	Architecture, Engineering, and Construction
AR	Augmented Reality
BIM	Building Information Modeling
BRIEF	Binary Robust Independent Elementary Features
CAVE	Cave Automatic Virtual Environment
DLP	Digital Light Processing
HMDs	Head-Mounted Displays
LPT	Luminous Planning Table
ICP	Iterative Closest Point
ICT	Information and Communication Technology
IVR	Immersive Virtual Reality
MR	Mixed Reality
PROCAM	Projector-Camera System
FAST	Features from Accelerated Segment Test
SAR	Spatial Augmented Reality
SIFT	Scale-Invariant Feature Transform
SURF	Speed-Up Robust Features
UWB	Ultra-Wideband
VR	Virtual Reality
RFID	Radio-Frequency Identification

Chapter 1 Introduction

1.1 Research Background

1.1.1 Collaborative Design

Collaborative design is an endeavor that involves people's connections to exchange ideas and coordinate design activities and resources. Design usually includes several individuals or groups participating in the design phase, particularly for a complicated and large project. Design collaboration is to exchange knowledge, concepts, expertise, or obligations. And design communication is essential to the concept of collaborative development. In exchanging design knowledge, decision-making and organizing design activities, the efficiency of design contact becomes crucial for designers (Chiu, 1998). Design experience has evolved over the last decade owing to globalization and computerization.

1.1.2 Architectural Design Collaboration

Architects frequently coordinate with peers and other relevant professionals and disciplines to address difficult problems and encourage the creativity of architectural designs beyond the capability of an architect (Cuff, 1992; Kalay, 2004). Architecture design is a dynamic collective activity, and its complexity arises from the essence of the design issue itself as well as the participants' interaction. In actual building projects, technological, legislative, and financial issues have grown more complicated, and the demand for specialist expertise for each issue field has, therefore, increased. Therefore, the quantity and quality of knowledge and expertise needed to complete the project is way more than can be dealt with by only one person. The expanded complexity of architectural design projects ultimately needs multiple specialists and non-professionals, such as architects, construction managers, engineers, financial planners, and policy, to cooperate (Lee and Jeong, 2012).

In the AEC industry, cooperation is remarkably fragmented, such that each discipline has established its own methods of expertise and representation. Architects are qualified to supply a defined range of activities with appropriate, productive, and aesthetic physical environments. By resisting or transmitting motions, moments, and inertia, structural engineers are trained to provide equilibrium. Via mechanical devices, mechanical engineers are trained to include functionality such as thermal stability and climate resilience. Construction managers are capable of determining a building's total constructibility. Such specializations also promoted their own mechanisms of interpretation and representation and even strengthened the symmetry of ignorance (Rittel et al., 1984; Lee and Jeong, 2012).

According to previous co-design research, one benefit of innovative collaboration emerges from shared information and stimuli created by differing perceptions and backgrounds of partners, such as task differences and multiple templates (Badke-Schaub et al., 2010). The shared information helps to recognize precious constraints and problem-solving schemes, and the shared design scenarios encourage new solutions (Basadur et al., 2000). Furthermore, developing innovative solutions through reflective cooperation, exploitation and appraisal of personnel are other benefits of collaboration. In collaborative architectural design, reflection-in-action takes note of the evolving solutions and the intentions and behavior of peers, which are expressed and criticized by each involved participant. The feedback obtained from other collaborators could cause new creative solutions or varieties that may have been missing earlier (Kalay, 2004).

In this context, representation is a method of information organization and communication for building project collaboration. The presentation used will greatly impact the outcome achieved in multi-disciplinary collaborative design. The representations of the numerous disciplines are

abstractions of fact internally developed in conjunction with their disciplinary interests. We decide the aspect of fact in which we are involved when selecting a representation. An architectural drawing, for example, is an abstract depiction of a certain fact. It does not contain all the features of that fact, only those that are applicable to a specific stage of design (Haymaker et al., 2000; Kalay, 1992). Therefore, representations created from different disciplines in a building project are very necessary, whereas one of the most understandable forms of representation is visual representation, which could also be called visualization (Goldschmidt, 2007).

That is to say, visualization plays a crucial role in architectural design collaboration. Effective visualization methods can facilitate the design thinking process, enabling practitioners to understand better and communicate their ideas (Sedlmair, Meyer and Munzner, 2012). In the context of architectural design, visualization is essential for assimilating knowledge, identifying relationships between different design components, and assessing the role and importance of visualization in the design process (Byundyugova, Корниенко and Kholina, 2020). Besides, architectural design often involves complex geometric reasoning and the ability to visualize and reason about physical objects and processes. Visualization allows designers to qualitatively increase the level of imaginative thinking, develop cognitive flexibility, and prioritize activities, which ultimately leads to increased efficiency and better design outcomes. Visualization technologies can also contribute to more effective knowledge assimilation and awareness of the relationships between different design elements, enabling designers to assess the role and importance of visualization in their work.

1.1.3 Visualization Technologies of Architectural Design

The usage of computing technologies has developed numerous distributed design environments in design practice. Many researchers have worked on how software with an interdisciplinary design team may create more valuable objects (Simoff and Maher, 1997; Chiu, 2002). By encouraging cooperation and consolidating project knowledge and rendering it available, collaborative tools promote teamwork.

Recently, the use of building information modeling (BIM) has facilitated close cooperation between different project stakeholders, including architects, engineers, contractors, and clients, during the design phases of construction projects (El-Diraby et al., 2017). The technical core of BIM consists of 3D imagery and information management for buildings (Wang et al., 2014). Since all the data is accessible in 3D, BIM could further promote the use of visualization as a method to exchange ideas and share knowledge within and amongst various stakeholders in a project, and some BIM viewer software is developed and available for users' communication (Johansson et al., 2015). Simulation tools such as DesignBuilder and Revit have proven to be valuable in this regard, allowing designers to explore the interplay between the building's form, materials, and the surrounding environment. (Kutlar & Mengüç, 2019) This collaborative approach to design modeling promises a new way to address the sustainable design process, overcoming the barriers that have historically hindered the architects' own adoption of these tools. (Hirsig, 2010)

Despite the advantages of visualizing architectural concepts using 3D models, existing BIM visualization platforms are not effective for sufficient design information sharing (Oh et al., 2015). In particular, even though 3D models could be built by BIM software, participants

would still have to image and map the models that are on 2D display mediums into the 3D real space, which relies on the spatial awareness of the participants (Meža et al., 2014). To address this issue, previous studies have attempted to promote the process of translating modeling data into a more intuitive physical experience by mixing simulated models with an actual environment (Meža et al., 2014). In this context, augmented reality (AR) has been introduced as an alternative visualization platform to effectively convey 3D models into realistic insights via the extended assistance of BIM visualization (Wang et al., 2014). AR is generally used to enhance real-world objects and spaces by using digital information (Berryman, 2012). In AR, data that stimulates and enhances the real world is presented and integrated into the user's observation (Ahlers et al., 1995), which shares resources between an AR display and users. These shared resources help to recognize relevant issues and inspire a new way of solution generation (Basadur et al., 2000; Hong et al., 2016). Due to these aspects, AR has also gained attention for design review and collaboration. AR is suitable for developing an interactive 3D communication environment for design, allowing users to explore the greater potential of design scenarios and the ability to evaluate 3D BIM models more intuitively before being physically built (Ko et al., 2011). Incorporating AR and BIM promotes collaborative attributes and realistic 3D visualization. AR also works as an extension or a supplement of BIM to immerse abstract 3D images into the user's view of the real world, which reaches a deeper level of reality (Calderon-Hernandez and Brioso, 2018).

Two types of AR display devices have been mainly used for design collaboration: (1) hand-held devices such as tablets and mobile phones, and (2) head-mounted displays (HMDs) such as Microsoft HoloLens (Azuma et al., 2001; Chen et al., 2015). Generally, in collaborative AR systems, virtual models displayed to users by hand-held devices or HMDs are consistent, and users can communicate with each other with details displayed on the screen (Nee et al., 2012).

However, existing AR display devices have been criticized for the drawbacks of (1) technical limitations of real-time tracking caused by the detecting sensors, (2) users' limited vision and uncomfortable wearing experience, and (3) unsatisfying visual quality of deviated perception and display issues due to screen display (Kruijff et al., 2010; Mekni and Lemieux; 2014; O'Hare et al., 2020; Park and Moon, 2013).

Recently, a new form of AR called spatial augmented reality (SAR) has been introduced to address these issues. SAR uses a digital projector to present graphics on physical objects to augment real-world objects and spaces, where display devices are separate from users, as opposed to the body-attached displays of AR (Bimber and Raskar, 2019). Moreover, SAR does not require additional expensive AR devices, and it uses visual registration to avoid the inevitable error of sensor detection. The device is also separate from users, which therefore avoids potential discomfort and provides ultimate stereo views since virtual objects are actually projected into reality. The truer view (without a screen display) could moderate false perception to a greater extent for users. Due to these aspects, SAR has a great potential to be used for architectural design visualization by projecting BIM images on 'tangible objects' such as small-scale mock-ups. Unlike see-through HMDs that visualize virtual information only from each user's view, the shared experiences using SAR can support better collaboration and communication between project participants during design collaboration. Additionally, design evaluation based on augmented 'tangible objects' such as small-scale mock-ups enhances users' understanding of design, allowing more efficient decision-making on various design alternatives.

1.1.4 Daylight Simulation for Architectural Design

The integration of nature and aesthetics is crucial in creating buildings that are both visually appealing and environmentally responsible. (Hu & Zhang, 2019). To be specific, on the one hand, one of the key challenges in architectural design collaboration is the ability to effectively visualize the impact of the building's exterior on the overall design, which plays a crucial role in ensuring the design meets the client's requirements and aligns with the overall aesthetic vision (Saleh et al., 2016). On the other hand, a critical aspect of this process is the consideration of environmental factors that can significantly impact the design and implementation of a project (Wagner et al., 2020). The relationship between nature and human perception is a key factor in this process, as the way people experience and interact with the built environment can be greatly affected by its natural elements (Ilvitskaya, Lobkov, and Lobkova, 2020). Also, design variables in early design stages, including shading area and building orientation, have an effect on a building's life-cycle environmental impacts. Therefore, daylight simulation could be beneficial for architectural design (Zhou et al., 2023).

1.2 Research Problems

Traditional AR typically handles 3D virtual models aligned directly with 3D real-world objects (3D → 3D registration). In contrast, SAR introduces an intermediate 2D step: 3D models are first projected as 2D images before being spatially mapped back to 3D (3D → 2D → 3D). This creates complexity in maintaining geometric accuracy and visual fidelity during conversions. Also, unlike existing virtual environment simulation in BIM that directly simulate the sun in the specific position, SAR that using fixed projectors to simulate the moving daylight could be challenging. Moreover, in terms of the importance of visualizing exterior design and environmental impact in architectural design collaboration, as previously discussed, more general research problems revolving around these two scopes are listed.

(1) The possibility of SAR for designing has been demonstrated in different fields, especially in the automobile area; there is a variety of research showing the design and projection mapping method and process on individual automobile design. However, the building appearance design is more complicated, and more detailed components are to be displayed. There is also a lack of introductory methods for SAR to be applied with BIM software.

(2) Projecting BIM images correctly onto surfaces of architectural foam mock-ups requires sophisticated computational processing for geometric calibrations (i.e., adjusting BIM images to fit the surface of a mock-up) of a projector-camera system. The complexity of existing calibration processes would hinder the use of SAR for BIM visualization in practice by limiting user experience and usability by building designers and other stakeholders.

(3) Visualizing the environmental impact is also significant for architectural design collaboration. Considering that building design images can be projected through a beam of light onto a physical model, it is expected that daylight simulation and visualization using SAR would create a more real-like environment simulating various lighting conditions for design review. In this regard, SAR has shown its potential for lighting design in wall interiors (Sheng et al., 2009), and more functional applications of SAR on architectural design, such as daylight simulation, could be developed. Also, the benefit of daylight visualization for building exteriors has not been fully investigated, compared with traditional daylight visualization using existing tools such as 3dx Max.

1.3 Research Objectives

This research aims to develop SAR-based BIM visualization that projects a BIM environment onto small-scale 3D form mock-up models for interactive visualization and collaboration during the design phase. The detailed objectives are stated as follows. Figure 1-1 illustrates the overall framework of this research.

(1) With the potential of SAR becoming a new visualization platform, collaborative design in the building industry would likely benefit from this technology as well, with the combined usage of the 3D BIM model. This integrated application of SAR and BIM for design collaboration has not been tested so far. Therefore, the first objective is to show the prototype of the SAR application on the appearance texture of an individual building model, combined with the usage of BIM software.

(2) In terms of the research conducted for objective (1), existing SAR (projection mapping) software only accomplishes manual geometric calibration to align the virtual building model with the physical model in the 3D real world. The complexity of existing calibration processes would hinder the use of SAR for BIM visualization in practice by limiting user experience and usability by building designers and other stakeholders. To improve the efficiency and intelligence of the SAR system for BIM visualization, this research aims to develop an automatic geometric calibration approach based on marker detection.

(3) Unlike projection mapping on 2D surfaces like walls, projecting daylight-simulated exterior building design onto a 3D building model is quite challenging due to the technical difficulty of aligning projectors for 3D surrounding visualization, the precision of simulated the daylight effect on building surfaces, and the tracking of movable 3D building model with simultaneous

daylight simulation. Therefore, the study aims to develop an integrated SAR system that allows dynamic daylight simulation for architectural design using fixed projectors.

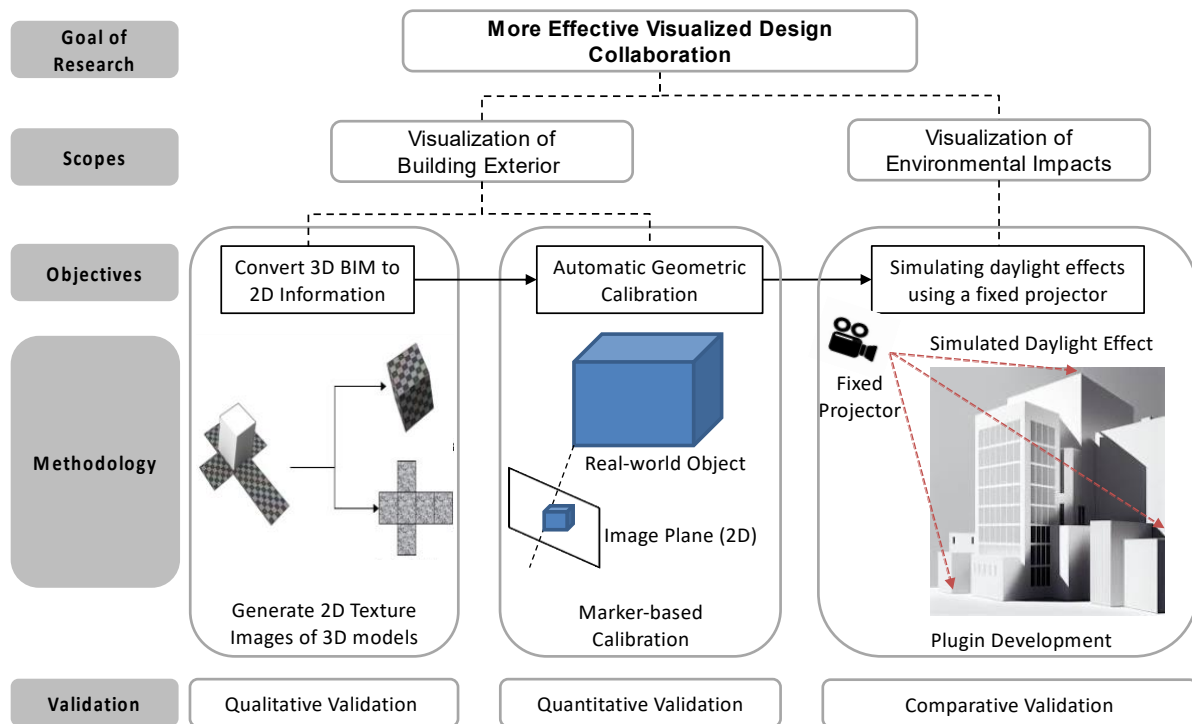


Figure 1-1 Research Framework

Research framework (Figure 1-1) presents a comprehensive approach to enhancing design collaboration and environmental impact visualization in architectural and construction contexts. For the scope of more effective visualized design collaboration, research applied tools and techniques for improving how designers interact with digital and real-world representations of buildings. On the one hand, it includes methods such as converting 3D BIM to 2D information, and marker-based automatic calibration, which enhances precision in mapping. The process bridges the gap between real-world objects and 2D image planes, facilitating smoother transitions between physical and digital design stages. Quantitative validation is used to evaluate, suggesting a data-driven approach to refining these visualization tools. For the scope

that visualization of environmental impacts, the study focuses on simulating natural daylight conditions to evaluate building performance. A fixed projector is employed to mimic daylight effect, enabling designers to study lighting effects in a controlled environment. The study also involves creating software extensions for existing BIM or design platforms. Comparative validation is used to benchmark results against real-world conditions or alternative methods, ensuring reliability.

Chapter 2 Literature Review

2.1 Augmented Reality

2.1.1 Overview

Augmented reality (AR) is a kind of mixed reality technology that enhances a user's perception of the real world through information provided by computer systems, which superimposes computer-generated virtual objects, scenes, or system prompts on real scenes to achieve the “enhancement” of reality (Wang, 2009).

Mixed reality has been formally defined as a particular category of technology associated with virtual reality (VR) in which physical and virtual objects are viewed jointly on a unified display (Milgram and Colquhoun, 1999). The concepts of Augmented Reality (AR) and Augmented Virtuality are the two key subsets in the MR spectrum, as illustrated in Figure 2-1 (Wang, 2009).

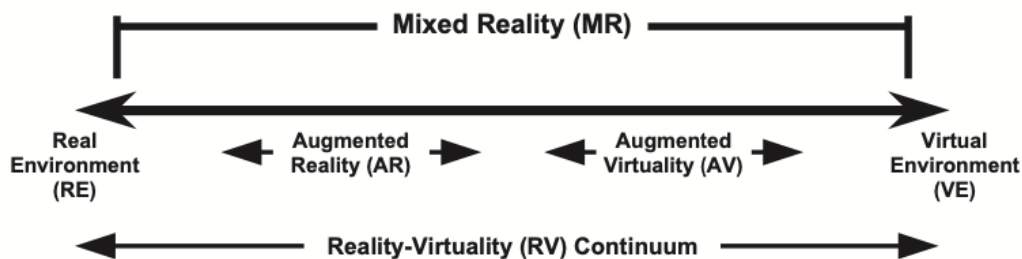


Figure 2-1 Reality-Virtuality Continuum (Wang, 2009)

In augmented, the additional information generated by a computer is inserted into the user's real-world view, while augmented virtuality immerses real-world display in a computer-generated environment (Milgram and Colquhoun, 1999; Azuma, 1997). By adding a virtual environment where users hold and engage with digital content in the actual space in which people operate, AR could build an augmented space. And by utilizing the visual and spatial

abilities of people, AR offers virtual data in the actual environment of the user rather than moving the user into a virtual world created solely by the computer (Wang and Dunston, 2006).

The demand for access to vast volumes of construction, engineering, and management data in the architectural and design industries provides prerequisites for the use of AR techniques, including relevant workers in the augmented workplace. The demand for access to vast volumes of construction, engineering, and management data in the architectural and design industries provides prerequisites for the use of AR techniques, including relevant workers in the extended workplace. And Human-computer systems that integrate an internal operating space with specific concepts or field knowledge can be an appealing technology class for the design and architectural industries (Wang et al., 2004).

2.1.2 Technologies of AR

(1) Display

Head-Mounted Displays

Head-mounted displays are displays used primarily by AR devices presently. There are two varieties of head-mounted display technologies for superimposing graphics over the actual world vision of the participants. One is video see-through display that utilizes video connectivity to show integrated images within the closed-view head-mounted display. Using real-time data transfers, a camera records a picture of the physical environment and stores it digitally. Afterward, the graphics processor merges the live video stream with digitally created pictures, also known as virtual content, and presents it to the viewer. Another is optical see-through display, which uses optical mixers that are mainly half-silvered mirrors or translucent LCD displays (Rolland et al., 1995). In order to view one's immediate environment clearly, a significant quantity of light from the outside world may travel through the mirror. Concurrently,

a display component mounted on the ceiling or the side projects computer-generated pictures onto the mirror, resulting in an impression of the integrated environment.

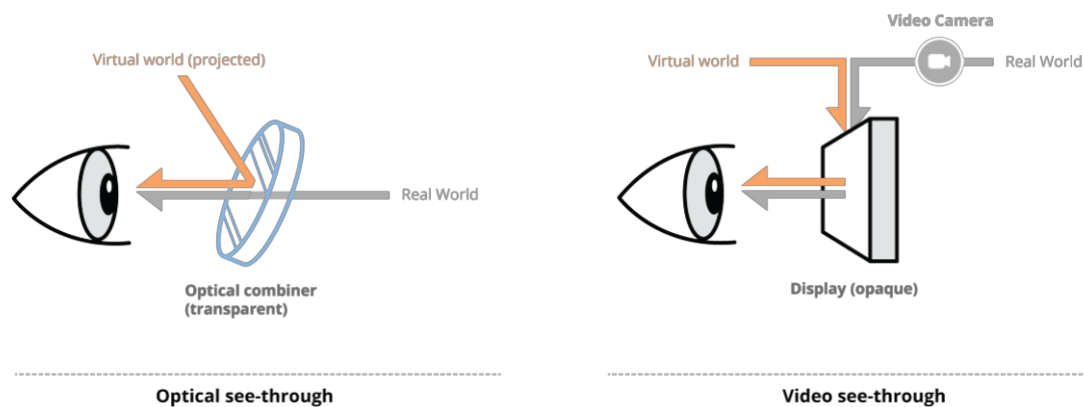


Figure 2-2 Principles of optical see-through display and video see-through display (adopted from Zhou et al., 2020)

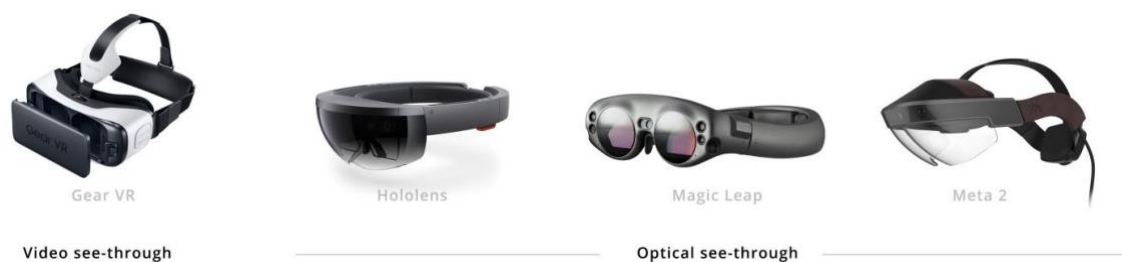


Figure 2-3 A visual classification of popular video and optical see-through display headsets in the market (Yadev, 2018)

Handheld Displays

An AR application can leverage the tablet form factor to display a video stream from a camera attached to the Tablet PC with real-time augmentations (Schmalstieg and Wagner, 2007). Conventional representations of hand-held displays, such as tablets, personal digital monitors, or more modern mobile phone screens, produce easily accessible images within the reach of arms. All these instances incorporate the integrated processing unit, storage driver, monitor and

interaction hardware into one system and strive to enable unrestricted and wireless mobile handling (Fruend et al., 2001; Mohring et al., 2004).



Figure 2-4 Smartphones, PDA and Tablet PC are used as the Handheld display of AR (Schmalstieg and Wagner, 2007)

(2) Localization

Localization is a way of discovering the actual or relative location and orientation in a real environment or in a computer representation of a working place or facility in the user's equipment. Localization techniques can be classified into two groups: marker and markerless (Mahmood et al., 2020). For the former, synthetic markers such as ID markers, QR codes, infrared markers, and natural markers used to classify the natural attributes of objects or surrounding regions have been applied. For the latter, the commonly used technologies are global positioning system (GPS) by sensors, photogrammetry originated, ultra-wideband (UWB), Radio-Frequency Identification (RFID) and laser scanning (Liang et al., 2011).

(3) Registration

Registration is a procedure of aligning visual data with other visual data, such as a picture and a point cloud. The registration method typically matches features such as local feature descriptors or geometric features derived from visual data by computing the transformation to

superimpose one on the other for visual data matching, where localization results are normally used for this procedure (Mahmood and Han, 2019).

2.1.3 AR for BIM-Based Architectural Design Collaboration

Previous research efforts have demonstrated the possibility of combining AR and BIM for architectural design collaboration. Fukuda et al. (2015) conducted an experiment using AR simulation with real-time video played on a laptop displayed in Figure 2-5, where 3D models were superimposed in an on-site scene to foresee the conditions of the constructed buildings. An auto AR system developed by Oppermann (2015) can visualize 3D BIM models on building sites in live videos using a head-mounted display and position-detection sensors to establish a real-time precise overlay of building models on a real site, as shown in Figure 2-6.



Figure 2-5 AR on-site foresee of the constructed building (Fukuda et al., 2015)



Figure 2-6 Auto AR system allows the user to experience virtual building models (Oppermann, 2015)

2.1.4 Advantages and Limitations

There are several advantages of applying AR technology in design collaboration. First, objects which do not exist in reality can be viewed and analyzed. Using an AR display, users can hold their individual views under their own control, and the displaced information can be adjusted in various forms (Billingshurst et al., 2009). For face-to-face design collaboration, AR could improve the information sharing of collaborative physical spaces, providing an interface for intuitive 3D interactive work assisted by computers. AR could also benefit remote collaboration. A study by Kato et al. found that AR offered substantially stronger co-presence and enhanced the immediate perception of communicative interactions (Kato et al., 2001).

However, despite the advantages of AR, several limitations have also been found. From a technical perspective, existing AR systems that use a tablet or head-mounted display require real-time tracking technology that relies on sensor detection to enable precise and effective registration while users are in motion. Within this framework, sensor errors may easily occur (Mekni and Lemieux, 2014). Furthermore, users may feel discomfort caused by holding a tablet or wearing a heavy head-mounted device (Park and Moon, 2013). As existing AR users see an augmented view through their own AR displays, it is difficult to build common reference points

between users when representing spatially-located virtual data, which as a result, hinders the common understanding of virtual information compared with a shared physical space (O'Hare et al., 2020; Wang, 2009). The quality of visualized information is still low due to the technical limitations of existing AR devices. For example, while using a head-mounted AR display (e.g., Microsoft HoloLens), low resolution, distortion, and limited field of view could lead to a false perception of visualized information. Brightness, contrast, and visibility are other screen-related issues that can significantly affect visualization quality (Kruijff et al., 2010).

2.2 Spatial Augmented Reality

2.2.1 Definition of SAR

The concept of spatial augmented reality (SAR) was developed from AR by replacing the display devices from monitor screens with projectors; therefore, SAR is also initially called projector-based augmented reality. Projectors are still a widely used medium for SAR, so projection mapping is currently also called it (Grundhöfer and Iwai, 2018).

Spatial augmented reality (SAR) provides the experience of augmented reality by changing the appearance of the physical world with an optical projector (Figure 2-7). Compared to AR technology, SAR separates the display technology from a user's body and embeds it into a physical model (Bimber and Raskar, 2005; Benko et al., 2014; Thomas et al., 2014). For SAR, the real world is augmented by a display that is integrated directly into the user's physical environment—not merely through the user's field of vision—to maximize the user's level of immersion (Park et al., 2015; Raskar et al., 1999). The images may appear in 2D, placed on a flat display surface, or may be 3D and float over a planar surface, or even 3D and float over an uneven surface. Seeing a design in a projection-based mixed-reality environment helps users to understand better how a virtual product actually looks in the real world. Moreover, not only

will users obtain an augmented display of various prototypes themselves, but they can also interact with their customers in a creative and improved manner (Siegl, 2018). It is also worth mentioning that when SAR is applied to moving objects, the position of those objects is required in real-time to facilitate dynamic mapping (Koizumi et al., 2015).

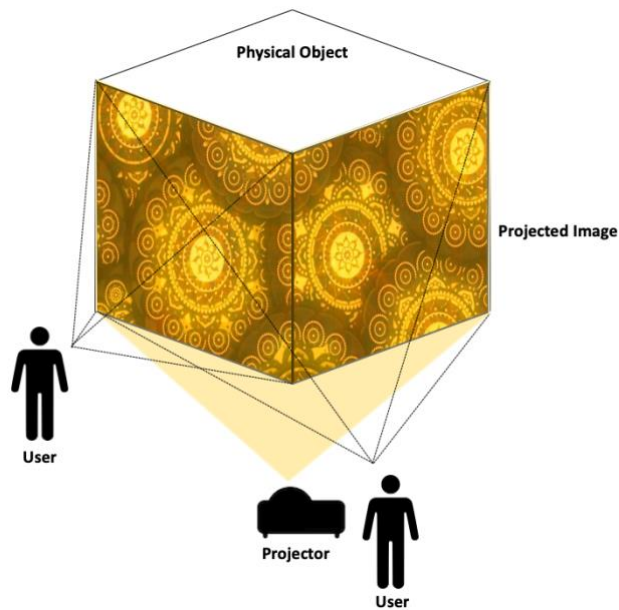


Figure 2-7 Basic Concept of Spatial Augmented Reality

2.2.2 Comparison Between AR and SAR

In comparison to the AR body-attached (head-attached or hand-held) display system, SAR utilizes spatial see-through displays. Spatial displays separate and incorporate much of the hardware from users into the world. Projector-based AR employs front projection to project pictures directly on the surfaces of real objects rather than on an image plane in the users' visual area. Fixed or movable single and multiple projectors are used to maximize possible projection areas and boost picture performance (Raskar et al., 1999; Raskar et al., 2001). Figure 2-8 illustrates various methods and media positions to present the augmented elements over the actual environment. In the early nineties, surround displays relying on projectors became

common. One of the most prominent is the CAVE, a multi-faceted, interactive projection space (Cruz-Neira et al., 1993).

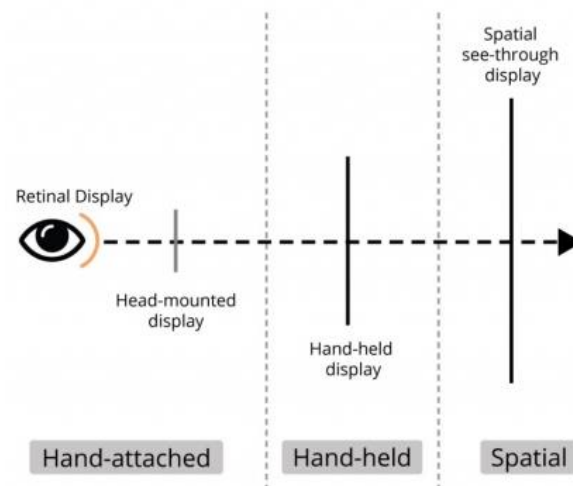


Figure 2-8 Various methods and the position of the display medium (Yadev, 2018)

Similar to AR, SAR also requires technologies for localization and registration. Localization is to find the geometric relationship between projected objects/surfaces in the real world and the projected models based on the relative location and projection angle of the projector. In the process, markers, GPS, laser scanning, photogrammetry originated method, et al. applied in AR, could also potentially be used in SAR as long as the targeted geometric relationship is clearly defined. Then, during the registration process, the defined geometric relationship is used for the physical alignment of every pixel in virtual models and the projected objects/surfaces in the physical 3D space. Table 1-1 shows the technological differences between AR and SAR.

Table 1-1 Technological differences between AR and SAR

	Localization and Registration Technics					Output display
	Compulsory registration	Getting the object's relative 3D Position in the real world			Feature matching by photogrammetry (applied only)	
		Sensor	Tracked Marker Point	Chessboard		
AR	×	✓	✓	✓	✓	2D screen
SAR	✓	✓	✓	×	×	3D Real-world

2.2.3 General Applications

The designed displays of SAR have been applied to various domains to explore how SAR systems can be applied to enhanced design mock-ups. In particular, there have been applications in the automotive industry that use virtual content to design and assess new components for cars (Menk et al., 2011). For instance, virtual content may be projected on a mass car model to help during a collaborative design session, as shown in Figure 2-9. Similar to the automotive industry, architectural design uses 3D building models to benefit from SAR technology for design collaboration. Verlinden et al. (2003) created a SAR system that combined the rapid prototyping of a physical model and an illuminating touchable interface for the aesthetic design of an automobile, as shown in Figure 2-10. The physical mass model of an automobile was placed on a turntable to offer rotational movement, and the tangible interface was projected on a vertical planar screen.

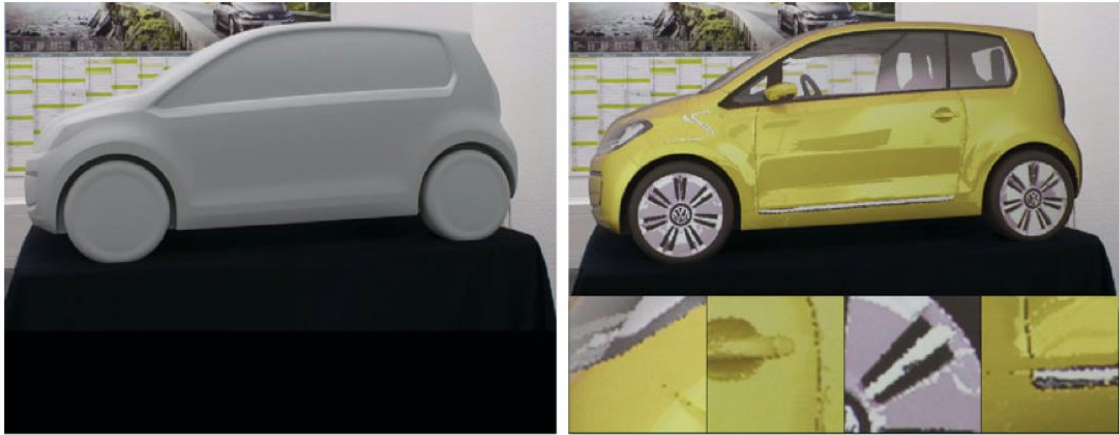


Figure 2-9 Projective texture on a car model (Menk et al., 2011)

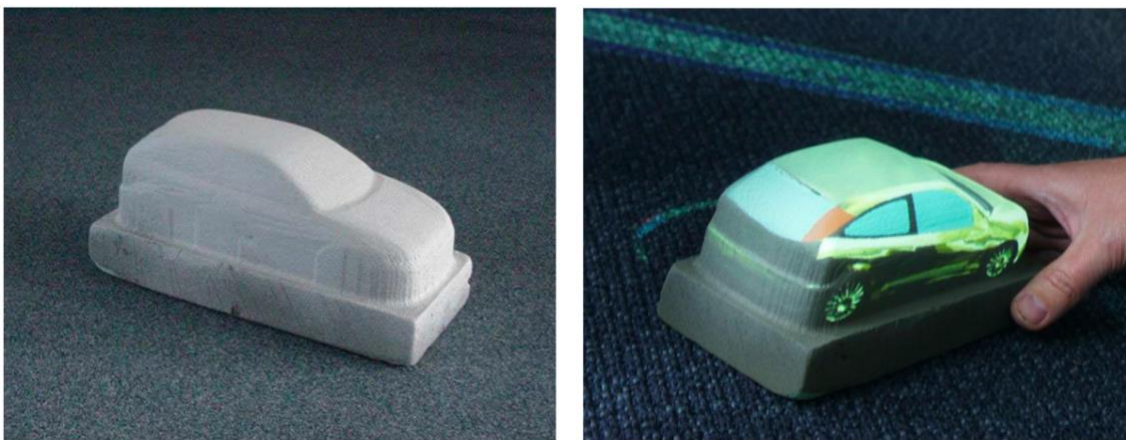


Figure 2-10 Typical foam model of a car augmented by projection (Verlinden et al., 2003)

Moreover, as displayed in Figure 2-11, Porter et al. (2010) applied the SAR system when designing an automotive dashboard. The dashboard's designs were fully projected on a mock-up model, and the texture could be changed to reflect particular design decisions. By changing the projection with the displays of several designs, users were able to compare and evaluate snapshots of possible layouts, even though the mapping did not have high fidelity. Von Itzstein et al. (2011) also demonstrated the application of SAR when designing appliances for an oven, where the design alternatives were projected quickly and easily on a real-scale oven, as shown in Figure 2-12. This application demonstrated that using SAR allows non-technical stakeholders to effectively take part in the collaboration process of a product's design. With the potential of SAR becoming a new visualization platform, collaborative design in the

building industry would likely benefit from this technology as well, with the combined usage of the 3D BIM model. Since this integrated application of SAR and BIM for design collaboration has not been tested so far, we have proposed a framework of BIM-based SAR for a detailed individual building design collaboration.



Figure 2-11 The dashboard prototype is augmented with a leather interior (Porter et al., 2010)



Figure 2-12 Oven design projection (Von Itzstein et al., 2011)

2.2.4 Studies on SAR Applications in the Building Field

The notable experiments (Daniele, 2013) used projected digital video on physical architectural models to design a lighting display that can be appreciated directly without relying on mobile devices or screens (Figure 2-13).

Mateus et al. (2019) present a model that integrates SAR and AI algorithms within a 3D urban model, using data from OpenStreetMap to process and indicate path optimization for a city area (Figure 2-14).

Mine et al. (2012) apply SAR to Disney Theme Parks that enhance the theme park experience by immersing guests in magical worlds. Figures in attractions are augmented and animated using projected media, and many new attractions being built or designed incorporate SAR features (Figure 2-15).



Figure 2-13 Mock-up projection of a building wall (Daniele, 2013)



Figure 2-14 Physical model with the projection of the city model over the wooden structure (Mateus et al., 2019)



Figure 2-15 Projection augmented Cinderella's Castle at the Magic Kingdom Park (Mine et al., 2012)

2.3 Geometric Calibration of SAR

2.3.1 Geometric Alignment

Traditional augmented reality uses goggles or monitors to overlay images onto the real world. These displays typically track objects, often using cameras and computer vision due to their flexibility. Because the real objects aren't altered, standard computer vision methods work well. However, using projectors to display graphics directly onto surfaces significantly changes object appearance, necessitating new techniques (Audet et al., 2013).

When projecting 3D virtual objects, there are many variables: user and projector position, front or rear projection, planar or non-planar display surface, and the virtual object's location relative to the surface. The proposed framework adapts to all these configurations, but geometric alignment between the projection and the real-world objects is crucial.

2.3.2 Geometric Distortion

(1) Keystoning

Projectors are common presentation tools, especially portable LCD projectors. However, if the projector isn't aligned correctly with the screen, the projected image will be distorted, a

phenomenon known as keystoneing (Foley et al., 1996), as illustrated in Figure 2-16 Keystoneing is problematic because it distracts viewers and distorts visual information like graphs, charts, and technical drawings, making them harder to interpret.

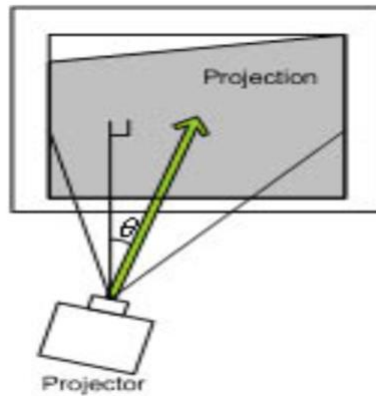


Figure 2-16 keystoneing effect occurs due to the projection angle between the projector and the projection surface (Park and Woo, 2006)

Keystoneing can be avoided by positioning the projector perpendicular to the screen and ensuring the image isn't rotated. This is manageable for fixed projectors, but portable projectors need alignment every time they're used. Manual alignment is tedious and sometimes impractical because the ideal projector position might be inconvenient (e.g., in the middle of the audience) (Sukthankar and Mullin et al., 2000).

(2) Radial Distortion

Radial distortion, a consequence of imperfect lenses, is prominent in wide-angle projectors. These projectors offer advantages for immersive environments by minimizing shadows due to their close placement to the screen. However, this benefit comes with significant image distortion, necessitating pre-distortion of the output image. Lens distortion refers to any deviation from the pinhole perspective model. While all lenses distort to some degree, wide-

angle lenses exhibit more noticeable distortion. Correcting for this distortion improves calibration, especially in wide-angle devices, by accurately mapping the projection of pixels onto real-world points (Johnson et al., 2007; Andrew, 2001).

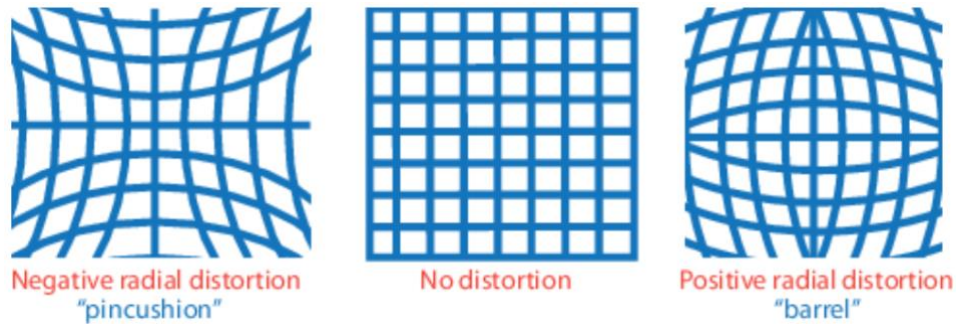


Figure 2-17 Radial distortion (Nenovski and Nedelkovski, 2018)

2.4 Existing Geometric Calibration Methods

2.4.1 Sensor-based Technology

Mobile augmented reality systems use sensor-based technology to obtain current location information based on the sensor positioning function, and the orientation sensor determines the orientation of the mobile camera. By aiming the camera of the mobile device at the real scene, the virtual enhanced information is superimposed on the display of the mobile device (González et al., 2014).

The development of this system involves a variety of sensors in mobile devices, so the accuracy and stability of geometric calibration also depend on sensors. Different types of positioning sensors use a series of principles: Global Positioning System (GPS) (Behzadan et al., 2008), Radio Frequency Identification (RFID) (Benes et al., 2012), optics (Morgère et al., 2015). Since the sensor-based geometric calibration can complete tracking and registration with a variety of built-in sensors, it has the advantage of reducing the amount of calculation. However, there is

a problem of sensor jitter during the geometric calibration process because the sensor is susceptible to interference from external environmental factors.

2.4.2 Vision-based Technology

Vision-based Geometric calibration is developed on the basis of computer vision. It uses the camera on the device to process images or videos to obtain tracking information and, based on the tracking information, to determine the position of the virtual scene to be superimposed in the real environment (Bajura and Neumann, 1995). This technology can dynamically correct errors while registering with a combination of image processing and computer vision methods. It is currently the mainstream technology in the field of geometric calibration for augmented reality.

(1) Marker-based Method

Marker-based geometric calibration is used to place artificial signs in a real-world scene, and then the camera is used to recognize the signs in the image while combining the principle of camera calibration. It is highly robust and has low processing power requirements (Gandy and MacIntyre, 2014).

Early markers were square signs on a black-and-white plane, and the basic shape was mostly square, such as ARTag (Fiala, 2004) and ARToolKit-Plus (Wagner et al., 2006). With the development of this method, a regular dodecagonal 3D marker was designed with ARToolkit signs on each surface of the marker (Mohamed and Mohamed, 2012). This type of marker solves the occlusion problem under different viewing angles, but since the marker occupies a large space in the real scene, it is not suitable for use in very complex scenes. Also, colored signs are applied for marker recognition. The detection of the marker might be affected by the

similar colors in the scene, and the calibration cannot be completed when the logo is occluded (Belghit et al., 2012).

(2) Natural Feature-based Method

Natural Feature-based geometric calibration does not need to place markers in the real environment in advance but to use some natural features in the scene to calculate the camera posture information to complete the calibration. The process first extracts the feature point set from the template image and then extracts the corresponding feature point set from each frame of data acquired by the camera. And through the matching relationship between the feature point sets to determine the spatial position of the camera. In this method, the extraction and matching of feature points is the key to stable calibration. Feature point detection and matching methods are mainly SIFT (Scale-Invariant Feature Transform) (Lindeberg, 2012), FAST (Features from Accelerated Segment Test) (Viswanathan, 2009), SURF (Speed-Up Robust Features) (Bay et al., 2008), BRIEF (Binary Robust Independent Elementary Features) (Calonder et al., 2010).

2.4.3 Comparison of Geometric Calibration Methods

Due to the insufficient performance of mobile smart devices, there are higher requirements for the algorithm's instantaneity, robustness, and computational efficiency. In addition, this method cannot accurately locate the target under occlusion or in an environment lacking texture. At the same time, the calibration might fail due to blurred imaging when the camera is moving at a high speed (Cheng et al., 2017).

Table 2-1 Comparison of geometric calibration methods

Geometric Calibration Method	Advantages	Disadvantages
Marker-based method	- Good real-time performance, lower computational complexity than natural feature-based method - Highest accuracy	- Computational complexity is higher than the sensor-based method - Problems of occlusion in the tracking process.
Natural feature-based method	- Higher accuracy than the sensor-based method - No destruction of the integrity of the real scene - Wider application range	- Highest computational complexity - Bad real-time performance - High system delay
Sensor-based method	- Smaller delay - Highest real-time performance - Less calculation.	- Jitter problems - low accuracy - Difficult to calibrate - Easy to be affected by the environment

It can be concluded that sensor-based method has the lowest accuracy, even though it avoids a large part of geometric calculations. Also, the instability of sensors' signal transmission and the high requirement of the environment might easily affect locating performance. There is no constant real-time tracking requirement for the moving physical models in this study, so it is not necessary to take advantage of the high real-time performance of sensors. As for the natural feature-based method, similar to the current calibration method of SAR, it requires high computational complexity that may significantly extend calibration time. However, marker-based method has the highest accuracy, and the relatively low computational complexity could simplify the calibration process. And since there is no real-time tracking demand, the occlusion issue that occurred in the tracking process could be neglected. Therefore, marker-based method is most appropriate to apply in this study.

Nonetheless, marker-based calibration method has been widely adopted in AR, but it is still challenging when applied in SAR. The display equipment of AR is tablets of a head-mounted

display, where the display output unit is still on 2D screens, although it has a highly immersive experience. So, the image's location alignment is eventually operated in two dimensions. Unlike AR, SAR displays images of 3D objects in the real environment, which means that the actual 3D relative location alignment of objects and projected images is needed. Moreover, the display stream is synchronous with users' movement and observation for AR, while the display of projectors is completely separate from users for SAR. This also demands independent position information of projectors in addition to camera positions. The AR camera position could be joined with a display screen. To sum up, AR only needs geometric correspondence between cameras and objects, but SAR needs additional correspondence between cameras and projectors, projectors and objects.

2.5 Advantages of SAR-based BIM Visualization for Architectural Design Review

Architectural design review requires an iterative collaboration process among project participants, and thus effective information exchange is crucial for its collaboration performance (Singh and Wang. 2011). During the design review and evaluation process, understanding and communicating an architect's design intent can be improved by sharing well-visualized BIM models (Johansson et al., 2015; Lee & Kim, 2018). While it is still common to share BIM models through 2D systems (e.g., monitor screen or printed copy), various immersive VR and AR technologies are emerging as a new platform for architectural design visualization (Dunston et al. 2011). While VR can provide simulated virtual space in an immersive environment that user can observe, navigate, and interact with for reviewing virtual building model (Shiratuiddin and Thabet, 2011), AR can provide 3D building model presentation associated with a real environment surrounding users (Van Krevelen and Poelman, 2010).

Table 2-2 A summary of building model visualization techniques

Category	Virtual Reality	Augmented Reality	Spatial Augmented Reality
Capability	Fully immersive virtual environment experience	Connection between the virtual information and real-world	Integration between virtual projection and real-world
Required Devices	HMDs or Immersive Screen (e.g., VR CAVE)	HMDs or Mobile Phone/Tablet	Projectors & Camera for calibration
Advantages	- User-oriented immersive virtual environments (HMDs) - Easy to manipulate virtual environment - Portable Devices	- User-oriented immersive virtual environment (HMDs) - Easy to manipulate augmented information - Portable Devices	- Realistic visual presentation on physical objects (real world) - No need for wearable devices (HMDs) - Multi-user support with a single device
Disadvantages	- Potential discomfort from HMDs - Expensive immersive screen settings (CAVE) - No support for multi-users	- Potential discomfort from HMDs - Unsatisfying visual quality of semi-transparent augmented model - No support for multi-users	- Fixed projectors (usually not portable) - Time-consuming calibration process

Table 2-2 shows the comparison of different display devices for immersive VR/AR-based BIM visualization. VR and AR technologies highly rely on specific display devices, and their applications could vary depending on the purpose of their use (Milovanovic et al. 2017). Even though some AR applications can use tablets or mobile phones, fully immersive VR and AR applications have expensive setup costs. For example, one of the widely used VR systems, VR CAVE, requires an independent room with sophisticated tracking and projection systems (Aromaa and Vaananen, 2016). Recently, HMD-based VR/AR displays have gained popularity as relatively cheap consumer-level devices are available in the market (Dünser & Billingham, 2011). However, considering that all users need to wear optical see-through head-mounted displays (HMDs) for design collaboration, initial investment costs for purchasing multiple

HMDs may limit their applicability in practice. Also, wearing HMDs has shown several disadvantages of unsatisfying wearing experience (Park and Moon, 2013), inadequate quality of virtual objects visualization (Kruijff et al. 2010) and limited interaction for design collaboration (Wang, 2009). Especially the prolonged use of HMDs may cause users' visually induced motion sickness (VIMS) (Keshavarz et al. 2015). Since all users should use the wearable devices individually, it may not be suitable for the design collaboration in which multiple participants need to communicate based on the same building information (O'Hare et al. 2020).

Compared with typical VR/AR systems, SAR, which is a new form of AR, has comparative advantages, especially for collaborative architectural design review that involves multiple project participants (Bimber et al. 2005). SAR requires only digital projectors to augment a real-world environment with virtual graphics through projection.

Unlike optical see-through AR, SAR does not require expensive HMDs, enabling users to avoid uncomfortable wearing experiences. Also, multiple users can experience the virtually augmented real world from shared and wide field-of-views. By maximizing the level of immersion and reality, SAR allows users to understand better what a virtual design looks like in the real world (Park et al. 2015). Due to these advantages, previous research efforts have applied SAR-based design visualization for virtually enhanced mock-ups (Men et al., 2011). For example, Verlinden et al. (2003) created a system that combined the rapid prototyping of a physical model and an illuminating touchable interface for the aesthetic design of an automobile. Porter et al. (2010) applied the SAR system when designing an automotive dashboard by changing the projection with the displays of several designs, which enables users to compare and evaluate snapshots of possible layouts. Von Itzstein et al. (2011) also

demonstrated the application of SAR when designing appliances for an oven by projecting design alternatives on a real-scale oven mock-up. In the construction domain, Several studies have explored the use of SAR during the design process. For example, Ben-Joseph et al. (2001) proposed the ‘Luminous Planning Table (LPT)’ that projects diverse urban design alternatives on the top of a table for communication and learning during the design process. Chen & Chang (2006) suggested a SAR-based 1:1 scale visualization of interior design by projecting 2D drawings on site. Tonn et al. (2007) also applied SAR technologies to project planned interior designs onto surfaces of a real room at a scale of 1:1. Based on the user study, it was also found that SAR-based design visualization allows a more intuitive understanding of the design, especially for laymen. Milovanovic et al. (2017) suggested the concept of a design visualization platform using both VR and SAR technologies that project 2D plans or virtual mock-ups on the tabletop. Even though these studies have shown the potential of SAR for architectural design review, they relied on 2D-based projection, such as projecting 2D images on a wall or a plat tabletop. However, projecting 3D virtual architectural design onto surfaces of a 3D object, such as a real foam mock-up, requires more sophisticated calibration processes, which will be described in the following Chapters.

Chapter 3 BIM-based SAR for Architectural Design Collaboration: A Proof of Concept

3.1 Background

For architectural design, effective design collaboration is vital, as it helps to promote teamwork through encouraging cooperation, as well as sharing stakeholders' ideas and project knowledge (Gross et al., 1998). Architects often work with not only peers but also professionals from other relevant backgrounds to address complex problems that are synthesized by multidisciplinary issues. Effective design collaboration can foster more creative design proposals, which might not be possible with the limited capability of architects (Kalay, 2004). Recently, the use of building information modeling (BIM) has facilitated close cooperation between different project stakeholders, including architects, engineers, contractors, and clients, during the design phases of construction projects (El-Diraby et al., 2017). The technical core of BIM consists of 3D imagery and information management for buildings (Wang et al., 2014). Since all the data is accessible in 3D, BIM could further promote the use of visualization as a method to exchange ideas and share knowledge within and amongst various stakeholders in a project, and some BIM viewer software is developed and available for users' communication (Johansson et al., 2015).

Despite the advantages of visualizing architectural concepts using 3D models, existing BIM visualization platforms are not effective for sufficient design information sharing (Oh et al., 2015). In particular, even though 3D models could be built by BIM software, participants would still have to image and map the models that are on 2D display mediums into the 3D real space, which relies on the spatial awareness of the participants (Meža et al., 2014). To address this issue, previous studies have attempted to promote the process of translating modeling data into a more intuitive physical experience by mixing simulated models with an actual environment (Meža et al., 2014). In this context, augmented reality (AR) has been introduced

as an alternative visualization platform to effectively convey 3D models into realistic insights via the extended assistance of BIM visualization (Wang et al., 2014). AR is generally used to enhance real-world objects and spaces by using digital information (Berryman, 2012). In AR, data that stimulates and enhances the real world is presented and integrated into the user's observation (Ahlers et al., 2002), which shares resources between an AR display and users. These shared resources help to recognize relevant issues and inspire a new way of solution generation (Basadur et al., 2000). Due to these aspects, AR has also gained attention for design review and collaboration. AR is suitable for developing an interactive 3D communication environment for design, allowing users to explore the greater potential of design scenarios and the ability to evaluate 3D BIM models more intuitively before being physically built (Ko and Chang, 2011). Incorporating AR and BIM promotes collaborative attributes and realistic 3D visualization. AR also works as an extension or a supplement of BIM to immerse abstract 3D images into the user's view of the real world, which reaches a deeper level of reality (Calderon-Hernandez and Brioso, 2018).

Existing AR display devices have been criticized for the drawbacks of (1) technical limitations of real-time tracking caused by the detecting sensors, (2) users' limited vision and uncomfortable wearing experience, and (3) unsatisfying visual quality of deviated perception and display issues due to screen display (Kruijff et al., 2010; Mekni and Lemieux, 2014; O'Hare et al., 2020; Park and Moon, 2013). Recently, a new form of AR called spatial augmented reality (SAR) has been introduced to address these issues. SAR uses a digital projector to present graphics on physical objects to augment real-world objects and spaces, where display devices are separate from users, as opposed to the body-attached displays of AR (Bimber and Raskar, 2005). Moreover, SAR does not require additional expensive AR devices, and it uses visual registration to avoid the inevitable error of sensor detection. The device is

also separate from users, which therefore avoids potential discomfort and provides ultimate stereo views since virtual objects are actually projected into reality. The truer view (without a screen display) could moderate false perception to a greater extent for users. Due to these aspects, SAR has great potential to be used for architectural design collaboration.

3.2 Methodology

The proposed framework of BIM-based SAR for building design prototyping consists of two main parts (see Figure 3-1). The first process is creating virtual and physical 3D models, UV maps, and texture files. The next process is projection mapping implementation, which transforms videos or images into interactive displays on a target surface.

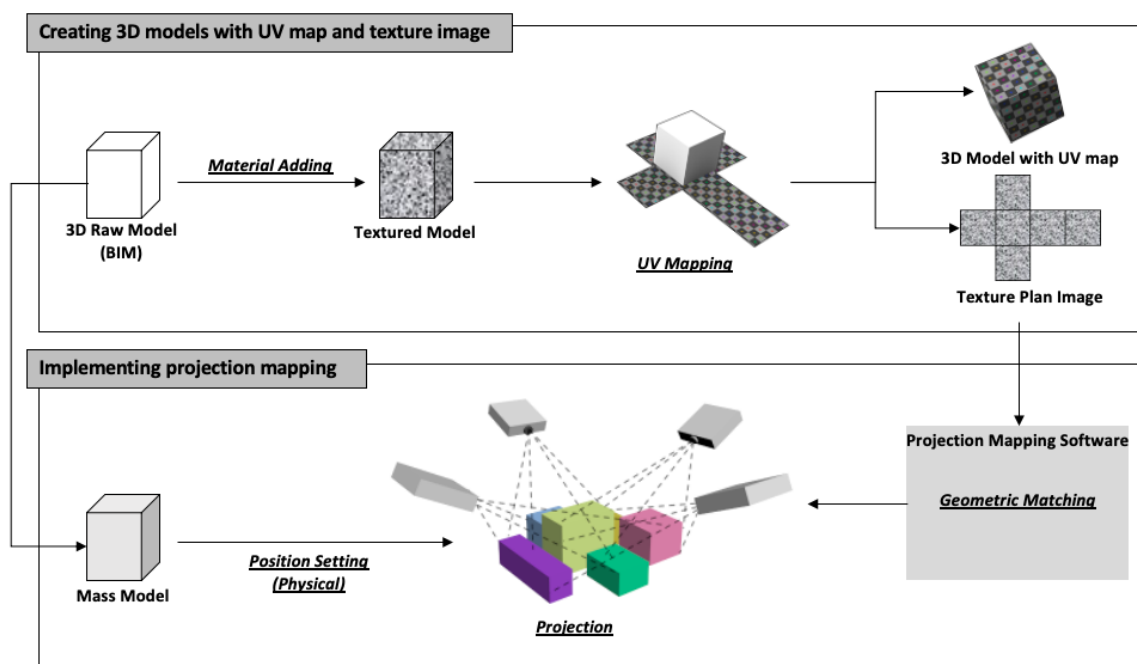


Figure 3-1 BIM-based SAR Implementation Framework for Building Design Prototyping.

3.2.1 Creating 3D Models with UV Map and Texture Image

The first step is to build raw 3D models without texture through BIM software. Even though there might be original material information when creating a 3D building model in BIM software, the material information in the BIM is only for the information delivery to indicate

the variety of designed material rather than actually including the colored texture to the model surface. To create a 3D model whose surface material could be projected on a real object by a video projector (Disguise), a material adding or texture mapping procedure is required, either in the BIM software or 3D animation and rendering software. For example, the process of applying material to the object's surface could be further done using the same BIM software, Revit, after completing the raw 3D building model (AutoDesk). Meanwhile, to create physical mass models as the base of projection, white-colored physical mass models are made in proportion to the 3D building model.

The next step is to create UV maps and texture image files. UV mapping is the process of translating a 3D surface with volume and shape onto a flat 2D image, where the 2D image is referred to as a UV map (3D Coat). The U and V refer to the horizontal and vertical axes of the 2D space, as X, Y and Z are already used in 3D space. During the UV mapping process, a polygon mesh needs to be produced, which is the collection of vertices, edges and faces that make up a 3D object. After producing the polygon mesh, the seams on which the unwarping is based will be clearly defined. This step is normally automatically processed by UV mapping software. A UV map can either have material texture, which can be used straight as the texture file, or without material texture, in which the texture file should be drawn based on the defined edge curves in the UV map. Furthermore, the UV map can be added to the raw 3D model, which is stored in the same file as the 3D model and can also be exported as an image file.

Depending on the software chosen, there might be a few ways to produce a UV map with the corresponding texture file of a 3D model. In this context, the software could have integrated functions of UV mapping, material adding, and 2D painting. There is existing software that offers professional and convenient material adding for building design, and the entire

complicated building texture is not easy to draw in a UV map. Therefore, as shown in Figure 3-1, the way we suggest is to add the material to 3D models to change the surface appearance before the UV mapping process to add color, detail, and texture to the 3D objects created in the 3D modeling software. Therefore, both the UV map and texture file would be generated by UV mapping a material-added 3D model. Commercial software, such as Autodesk 3ds Max and Blender, provide both functions of material adding and UV mapping. The texture baking function might also be provided in this software to generate the texture file of a 3D object whose material is added by other software such as Unity (Disguise; AutoDesk). In addition, a supplemental method could be used if the textured model is not fully prepared or there are slight changes in the designed texture. Since a 3D model is clearly unfolded at the seams and laid out flat on a 2D plan, once the UV mapping is complete, users can produce a custom image on the “pattern” of a UV map through 2D painting. This is similar to filling the color chunk on the UV map, which is linked to the respective area of the building model. This process makes it possible to produce models that are rich in color and detail with graphics software such as Photoshop. It is worth mentioning that Blender could also perform texture painting on the UV map, and textures can be displayed on the 3D object in the meantime (Hassan, 2016; Mullen, 2011).

3.2.2 Implement Projection Mapping

Appropriate hardware and software are required to implement projection mapping. There are several types of commercial software with projection mapping that are compatible with 3D models with UV maps and texture images. Users should choose the appropriate software according to their computer configurations, such as operating system (Windows/Mac/Linux), processor (CPU), graphics card, etc. The throw ratio of projectors should also be evaluated in advance—according to the prospective magnitude of mass models and the size of the experimental space—to have a proper image size under certain ranges of throw distance.

The proper position and connection of the equipment should be ensured for accurate projection mapping. The projector and the physical model must be placed where the projector throw can perfectly cover the target physical model. Additionally, a clear connection between equipment should be prepared to provide high display quality; a VGA port or HDMI port is generally utilized.

Geometric matching is the most essential process for accomplishing projection mapping. This step includes building a geometric correspondence between virtual images and real objects to relate the points in the coordinate system of the images to the real-world coordinate system. In a nutshell, the elements of angles and size of projected virtual images should be matched to be projected at the right designed position on the real mass model. Finally, the accurate projection of the model image can be presented on the physical model based on the results of geometric matching.

3.3 Results and Discussion

3.3.1 Case Procedures of BIM-Based SAR

In terms of the methodology stated in section 3.1, the first step was to create a 3D building model, UV map, and texture file. The 3D raw model of a four-story building was built in Autodesk Revit and exported as a .FBX file format, which is compatible with Autodesk 3ds Max. The material information was added to the raw building models in Autodesk 3ds Max. The UV maps and texture plans were also generated in this software, as shown in Figure 3-2(a–c). The UV maps could be added to different 3D model file formats, compatible with the projection mapping tools, and the texture plans were exported as image files.

Then, two-size mass models were made as the same proportional size as the virtual building model, where the proportion of dimensions is 78:79:100. The mass models were made of thick white cardboard, and the size of the two mass models are $8.3 \times 8.4 \times 10.1$ cm, and $5.8 \times 5.85 \times 7.4$ cm, respectively. The MadMapper was selected as the projection mapping software. The projector selected was Optoma ML550 with a throw ratio of 1.5/1 (D:W), which is suitable for the mass model size. This case study was conducted with the PC with Intel(R) Core (TM) i5-8250U CPU, 8 GB installed RAM, 256 GB SSD, Intel(R) UHD Graphics, and Windows 10 (64bits). The connection port used between the PC and projector was HDMI.

The next step was to set up the position of the projector and the mass models. The "Show Test Pattern" function in MadMapper ensures the model is fully covered under the projection area, as illustrated in Figure 3-2(d). Then, the virtual raw model file, which was attached to the UV map and texture file, was imported. The results displayed on the input channel in MadMapper are shown in Figure 3-2(e,f). The file format of the 3D model should be the OBJ file due to MadMapper's compatibility requirements. In MadMapper, virtual textured models can be moved, zoomed in or out, and rotated in the control panel.

The last step was geometric matching and projection. Geometric matching was proceeded by using the calibration function of MadMapper. It offers a manual calibration method that matches six points in the virtual model on the control panel of MadMapper with the corresponding six points on the physical mass model. As a result, the six points in both the virtual model and physical model can be marked and connected through a red line emitted from the projector (see Figure 3-2g). After matching the six reference points, the projected model image was automatically dragged to the expected position on the mass model, with the virtual model being dragged to the pointed position in the software panel. Moreover, micro

adjustments could be further performed manually at the matching point to trim the image to fit the object edge perfectly so that the projection could be achieved.

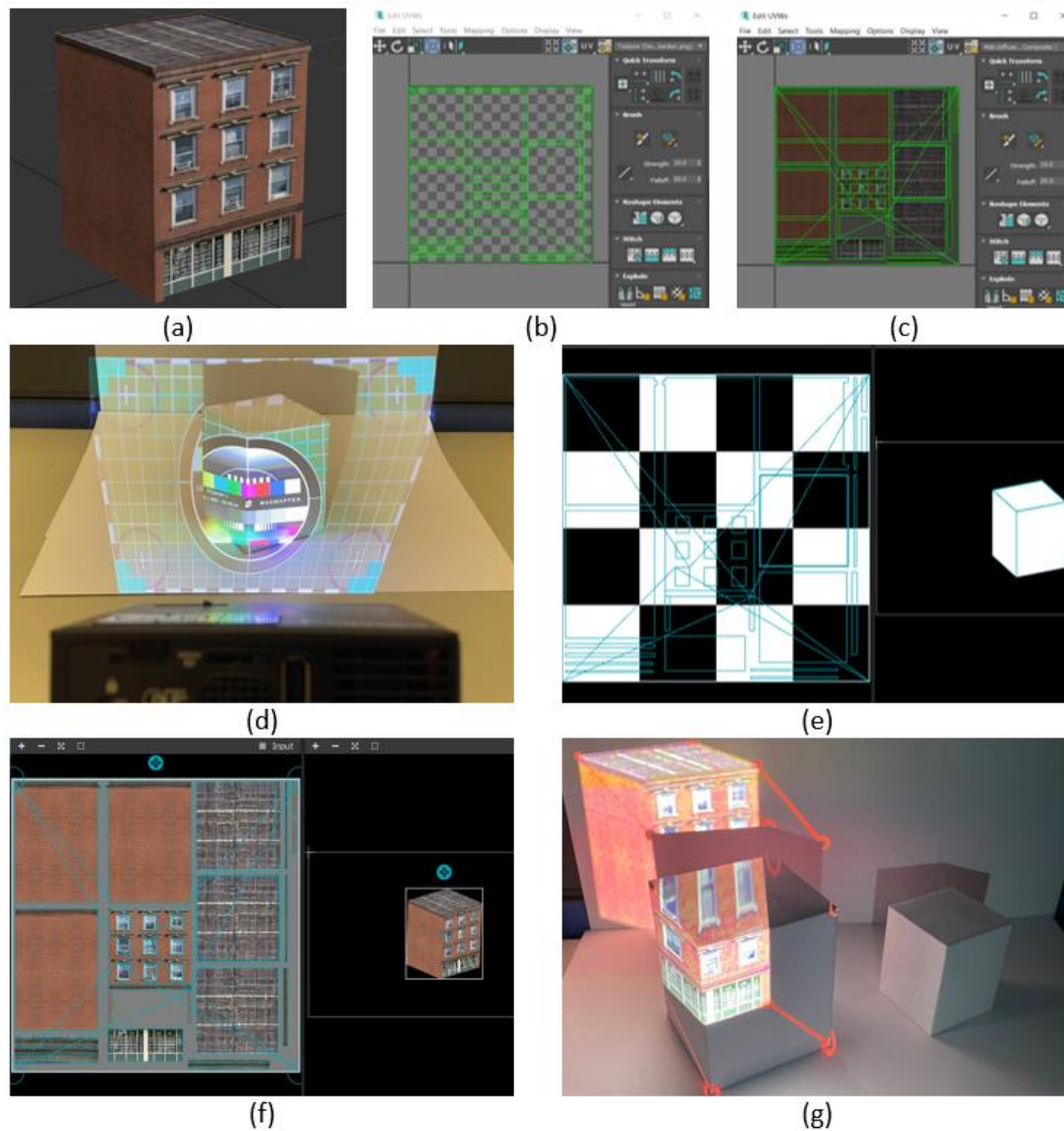


Figure 3-2 Case procedures. (a) 3D building model with material added; (b) UV map generated in 3ds Max; (c) Texture plan generated in 3ds Max; (d) Setting projector and physical model; (e) 3D raw model with UV map in MadMapper; (f) Textured model in MadMapper; and (g) Geometric matching

As can be seen in Section 3.3.2, the realness level of the projected model and the similarity to the designed virtual model were satisfied. Although the imaging throwing technology of the projector is one of the core factors that would affect projection quality, the medium-class

professional projector we selected for this case study was good enough overall to present the 3D model clearly and vividly. (Due to the working mechanism of the digital light processing (DLP) projector, there will be banding or line flicker when shooting the projection. Therefore, the captured results have nonnegligible anamorphosis from the actual scene observed by the eyes, and the performance is better for in situ observation).

3.3.2 Control Group Design and Results

To investigate the influence of the individual element on the performance of projection mapping, several elements in the proposed framework were tested for qualitative analysis. The selected control elements are mass model size, illumination condition, projection angles, and planar/curve projection surface. The explanation of setting and projection results are presented as follows.

(1) Mass Model Size

As described in Section 3.3.1, two types of model sizes were made; the augmented results are shown in Figure 3-3. The bigger model displays more clearly where there is dense detailed texture, such as the contents behind the window, glass door area, window frame texture, and sill. During the projection calibration process, the six reference points of the bigger model could be more precisely matched, which led to higher calibration accuracy. In addition, since the micro adjustment of one reference point would also slightly change the monolithic angle and distortion of the projected model in order to be consistent with the original geometric shape of the design model, there was less change and distortion in the bigger model and it was easier to operate.

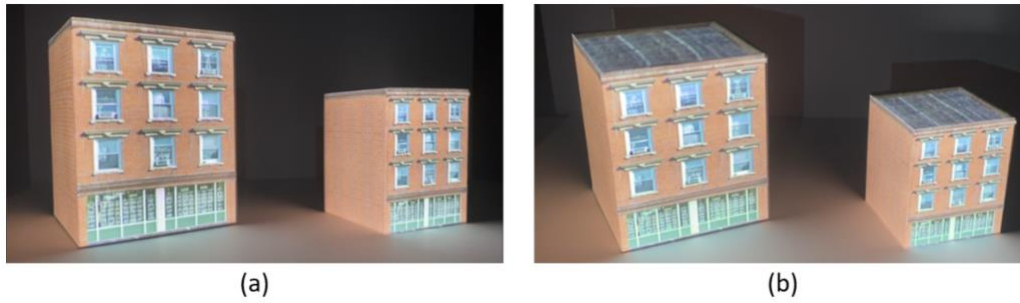


Figure 3-3 Comparison of projection results in two model sizes, (a, b) images shot from different angles.

(2) Illumination Condition

Two types of illumination conditions were simulated: with background light and without background light (see Figure 3-4). The biggest influence of lighting conditions on the projected image was color. The virtual image appeared to be closest to the original color scheme when the projection did not have background lighting. There was a higher degree of color contrast in the darker environment (no background lighting), especially on the lines and ridges of the model, such as the brick seams and window frame edges, which gave the projected model more depth and a stereoscopic effect.



Figure 3-4 Comparison of projection results with illumination condition. (a) Projection with environmental electric light; (b) Projection without environmental light

(3) Projection Angles

The relative angle between the mass models and the projector was changed by rotating the models horizontally (see Figure 3-5). This session illustrates the influence of tangential

distortion (keystoning) when the projected object has an angled surface. The projector was placed to throw the images more parallel to the front wall of the building model in a horizontal direction (as shown on the right side of Figure 3-5). When the building model was rotated horizontally to a certain angle (as presented in the left side of Figure 3-5), differences in projection could be detected. From the displays on the frontal wall of the building, the details seemed blurrier after rotation. Moreover, a relatively big difference caused by tangential distortion can be found in the flank wall, where the texture of the wall is projected much more clearly on the left-hand side of the figure.



Figure 3-5 Comparison of projection results in different projection angles.

(4) Planar/Curve Projection Surface

The planar and curve projection surfaces were tested in order to be compared. The tested models were made as a cylinder type and cube type by applying several textures of building materials on them (Figure 3-6). The typical building textures, such as brick, stone, and column patterns, were projected on both planar and curved surfaces. On the curved surface, there was a distortion issue, which affected the level of texture definition and slightly changed the design. Furthermore, there were discontinuous areas of the texture on the curved surface, but this was caused by the discontinuous part of the cylinder flank on the UV map. Likewise, the curved surface wrapping around the object might need to be separately placed on the UV map, which will lead to discontinuity in texture. Moreover, on the transitional area of the curved surface

that cannot be projected on (Figure 3-6f), there was huge distortion, and the pixel quality deteriorated extremely close to the edge lines.

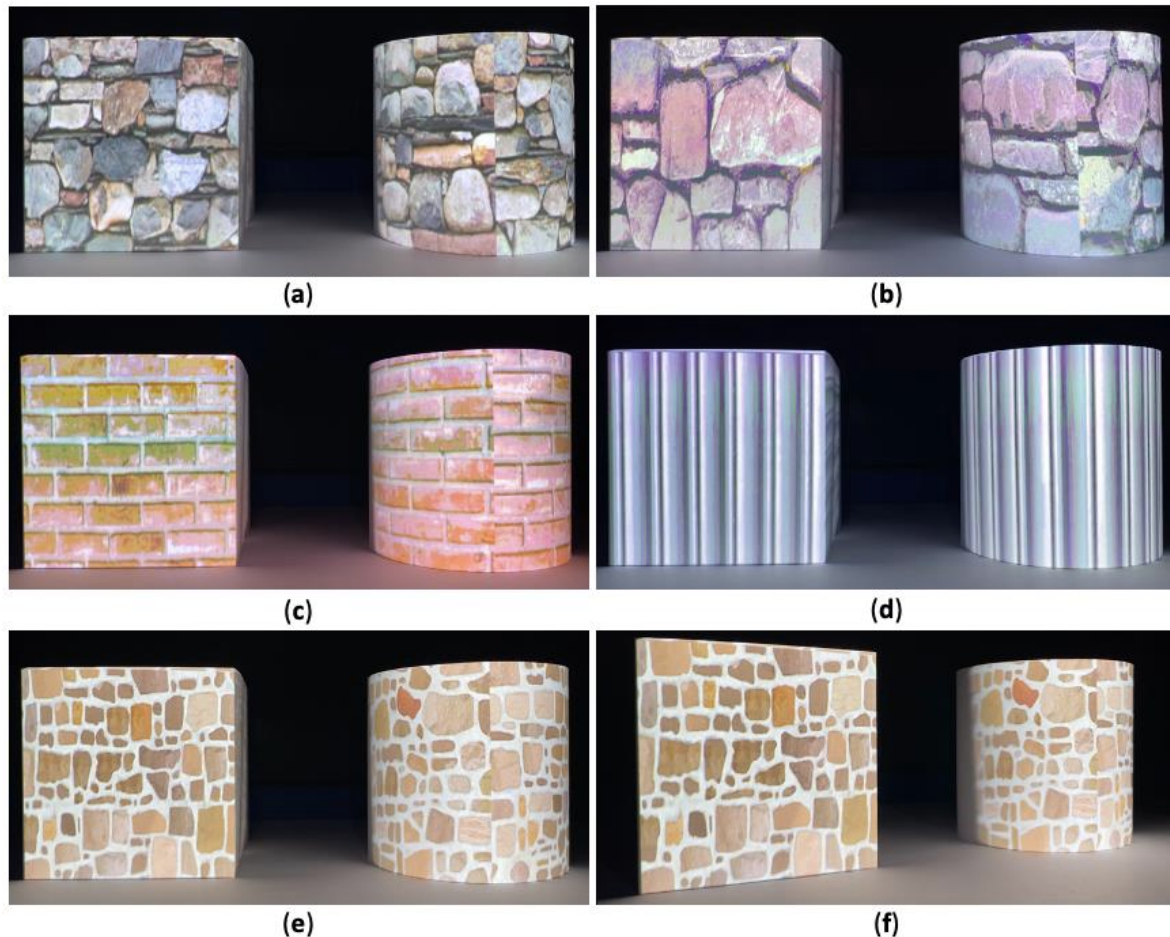


Figure 3-6 Comparison of projection results on planar/curved surfaces with various building textures. (a, b, e, and f) Building textures of stone; (c) Building texture of brick; (d) Building texture of column pattern

3.3.3 Discussion

We tested the feasibility of the proposed two-process framework by incorporating a projection mapping tool (i.e., the SAR rapid prototyping method) with a BIM model. Traditional AR relies on the sensor detection of the HMDs or hand-held devices for 3D position registration between the devices and the real world, leading to deviation results from sensor errors during operation. However, with the BIM-integrated SAR approach proposed in this study, 3D position

registration is achieved through reference point assignment between the virtual and physical models in the real world. Once registration is complete, the corresponding 3D coordinate information provides a stable and accurate projection output without the need for a wearable device or a continuous signal transmission from the sensors.

The use of this method for design review has great potential to provide a more interactive and intuitive means of design visualization. During the design review process, there could be several scenarios of the building design to be displayed, such as different materials of the building, positions of building components (e.g., windows), and overall structural designs. These design alternatives can be quickly projected on a physical mass model of a building, supporting collaborative design between project participants. For example, textured models of varying design alternatives can be generated and visualized one by one using a projector during collaboration, allowing more interactive design comparison. If needed, users are able to make a change in building design using BIM software, which can be simply and quickly inserted into the projection mapping software, and thus, the updated design alternatives can be shown promptly on the physical model. For this process, only the presenter needs to operate the equipment, and the users do not have to hold or wear any devices during design collaboration activities. As a result, non-technical users can easily and intuitively review building models without feeling the discomfort or dizziness of wearing an AR device. Users can even move around to view models from different angles, similar to how a real building would be observed. According to the results of qualitative analysis in the case study, high-quality details from various perspectives were easily observed, such as areas with a lot of visual content and the building model edges. Through the proposed methodology, project participants could also share a common reference point in the projected SAR environment. This could potentially be

beneficial for effective model-based collaboration between participants since it would enable them to communicate face-to-face with a shared view of the model.

However, some challenges remain when using the projection mapping tool for design collaboration. First, manual matching with at least six reference points (the basis of a stereo object) is only suitable for simple models, such as a cube. Certain building models may have a very complicated structure that contains many interleaved edges and a variety of small components of various shapes. In such cases, with more reference points being required for better matching, manual calibration would not be suitable, and a number of the components might not perfectly match due to their complex structures. Second, for projects with numerous design alternatives, especially with replaced physical models or where the design is frequently changed, manual calibration might also be inappropriate since recalibration of the reference points would be required. Third, when constructing a 360-degree view of a building model, edge blending might occur if there are overlapping areas from multiple projectors. Finally, tangential distortion (keystoning) caused by projectors being non-perpendicularly aligned to the object surface, as well as projection distortion on non-planar surfaces, needs to be overcome.

A projector-camera system is suggested to solve the aforementioned problems. Here, cameras are used as a proxy for the viewer to calculate the geometric correspondence between points in the projected images and the captured images of the object by the cameras, allowing the projected images to be aligned with the objects (Fujii et al., 2005). Geometric correspondence is generated by the calibration process of this system, while the calibration is self-forwarded (Li et al., 2017). Calibration methods such as those based on a checkerboard (Audet and Okutomi, 2009) and structured light have demonstrated the potential and speed of self-calibrated projector-camera systems to provide geometric information and deal with

registration issues, allowing them to accurately match the projected image of the object. Using such a system would avoid unnecessary manual calibration and achieve faster dynamic projection of design changes. By pre-wrapping the images in terms of the object information derived from camera scanning, automatic calibration of a projector-camera system could also handle keystoneing, blending issues as a result of using multiple projectors, and projection on 3D surfaces of complex shapes (Li et al., 2017; Sukthankar and Mullin, 2000; Chen et al., 2002; Sukthankar et al., 2001). Research into automatic calibration for projection mapping has been focused and evolved. However, the tools for automatic calibration are still being developed (Kourkoulakou, 2020), especially in terms of integrating different functions such as colorimetric correction, edging blending, and accusation of geometric information. At the same time, design software tools specific to the building industry also need to be developed.

In addition to the stated future studies, additional technical components need to be added to the proposed method for more interactive SAR building designs that would allow users to interact with augmented information, such as controlling the projected contents by gestures or other interactive mediums. For this functionality, a camera–projector system that enables tracking of a physical model and gesture recognition as an interactive medium could also be applied (Ren et al., 2011; Lapointe and Godin, 2005; Iannizzotto and La Rosa, 2007).

3.4 Conclusion

3D visualization technology, such as augmented reality (AR), has served as the display for building information modeling (BIM)-based architectural design collaboration to provide more effective design observation and communication for stakeholders. That said, AR has several technical limitations in terms of personal device issues, user experience, and visualization quality. A new form of AR called spatial augmented reality (SAR) has been introduced to

address these issues, which uses a digital projector to present graphics on physical objects for augmenting real-world objects. Therefore, SAR has great benefits and potential to combine with BIM for design collaboration. This paper introduces a BIM-based SAR operational framework, where 3D building models generated from BIM software are imported to projection mapping tools to display building surface textures on physical white building models. A case study using Revit and 3ds Max as the BIM software and MadMapper as the projection mapping tool was conducted to demonstrate the feasibility of the proposed framework and to evaluate the projection performance of SAR. The case study showed that the texture of BIM models could be projected on the objects clearly and realistically. Additionally, the proposed SAR method potentially offers intuitive observation of building models and a comfortable wear-free experience for collaborative design, and the qualitative analysis by changing the parameters was conducted to test the different projection conditions. Since it is expected that the use of SAR can be promoted by overcoming the discussed technical limitations and possible solution application, this study aims to trace the whole process of BIM-based SAR for architectural design collaboration.

Chapter 4 SAR-based 3D BIM Visualization through Automated Geometric Calibration of a Projector-Camera System

4.1 Background

Recently, Mixed reality (MR) technologies have gained attention for 3D BIM visualization as they provide a more realistic user experience in architectural design. When using a 2D screen as a visualization medium, a 3D BIM model is projected onto a 2D plain, somehow losing the sense of space. Instead, 3D visualization using MR technologies such as virtual and augmented reality (VR/AR) can enhance visual perception by merging virtual components with real-world objects (Speicher et al., 2019). Lee et al. (2020) compared different 3D BIM visualization mediums, including a 2D screen, a VR headset and an AR headset for architectural design review, and found that visual presentation quality (e.g., color, texture, size/location, naturalness) from VR and AR is significantly higher than a 2D screen. An AR-based BIM visualization provides excellent space perception (e.g., spacing, size and position). Despite these benefits of MR-based BIM visualization, current MR devices such as VR/AR headsets may have some limitations for collaborative design review by multiple participants. These devices only provide first-person views to users; thus, they would see the BIM model from their perspectives. Also, even though the price of VR/AR headsets is decreasing, the need for multiple headsets for collaborative review would be costly. Discomfort caused by prolonged use of headsets and eyestrain has also been commonly reported in previous studies (Lee et al., 2020).

To address these limitations, spatial augmented reality (SAR) could be a solution as an alternative 3D visualization medium for BIM-based design review. SAR, which is an AR technology based on projection (called ‘projection mapping’), can augment a real-world environment by projecting computer-generated virtual information (e.g., BIM models) directly onto the physical space or object (e.g., foam mock-ups) (Park et al. 2015). One of the advantages of SAR is that the AR environment can be created only by using existing beam

projectors without wearing HMDs, which may lead to dizziness or headache during their long-term use (Sharples et al. 2008, Grundhöfer and Iwai 2018). Also, unlike see-through headsets, SAR can provide shared AR experiences, supporting better collaboration and communication between project participants (Cortes et al., 2018). Additionally, design evaluation based on augmented ‘tangible objects’ such as small-scale mock-ups enhances users’ understanding of design, providing a better sense of space (Milovanovic et al. 2017). Despite these advantages, SAR applications in architectural design are still not typical, as projecting BIM images correctly onto architectural foam mock-up surfaces requires sophisticated computational processing for geometric calibrations (i.e., adjusting BIM images to fit the surface of a mock-up) of a projector-camera system. The complexity of existing calibration processes would hinder the use of SAR for BIM visualization by limiting user experience and usability by building designers and other stakeholders.

4.2 Geometric Calibration for SAR

Geometric calibration is the most significant technical component of SAR. It is to spatially align the designed virtual images emitted from a projector to the target physical object in the real world (Kourkoulakou, 2020). The augmentation display terminal is on 3D objects in the real world, while users can be moving or static. This process can be conceptualized based on both the micro viewpoint of pixels from the perspective of the smallest constituent unit of a projected image and the macro viewpoint of a virtual model, which is the entire appearance of the target object. In the three-dimensional space, either texture images are matched with objects’ surfaces pixel-by-pixel or the projected virtual model is in the same position as the physical model. The challenge is the spatial position coordinates of projectors and physical objects are uncorrelated in both viewpoints, so the coordinate systems of projected textures and objects

are independent. Building up the correspondence between these two coordinate systems is necessary to attain the alignment.

Calibration approaches of SAR can be generally categorized into manual calibration and automatic calibration. Manual geometric calibration adopts points matching between projected images and physical objects, in which the correspondence of projector and world coordinate systems is built fully by the judgment of human eyes. It basically drags images to eye-recognized positions manually.

Compared to manual geometric calibration, automatic geometric calibration explores the correspondence through machines or algorithms. It could intellectually exempt from the tedious labor work and reduce the potential manual operation errors. Since projectors and physical objects are apparatuses that do not know their own positions in the real world and do not have self-calibrated functions, mediums need to be applied when building up correspondence. Cameras have been used as a medium to develop SAR geometric calibration methods because of their strong detection and self-calibration ability. Various working mechanisms using a projector-camera system (PROCAM) in SAR development were created using different types of cameras, including RGB cameras and depth cameras. Currently, the typical steps of SAR geometric calibration systems can be concluded as follows:

- (1) Camera calibration to obtain intrinsic (e.g., focal length, principal point, lens distortion) and extrinsic (relative orientation of the cameras) parameters.
- (2) Projector calibration is used to generate correspondences between cameras and projectors to integrate PROCAM into one system.

(3) Projector-object calibration to estimate the real-world positions of physical objects with respect to projectors.

4.2.1 Some Current Automatic SAR Geometric Calibration Systems

Resch et al. (2015) calibrated the projector-camera system using the method adopted by Ouellet et al. (2008). Then, by applying the structured-light scanning method based on Yamazaki et al. (2011), a point cloud image of the physical object reconstruction could be obtained. Object-projector calibration is operated through the similarity transformation estimation (Umeyama, 1991) between the point cloud image and known object virtual model to calculate the transformation parameter between the projected model and object.

Kurth et al. (2018) built up PROCAM by finding pixel correspondences between RGB camera and projector based on the model of the Zhang method (Zhang, 2000). Afterward, a feature matching the object's tracked mesh generated from the depth camera and model image captured by the RGB camera is applied using the ICP algorithm. This is to compute the pixel correlation between the PROCAM system and the object to calibrate the projector and object.

In the SAR system developed by Cao et al. (2021), both RGB cameras and Inferred cameras were calibrated with a projector during the first geometric calibration phase. The calibration parameters of a projector-camera system (PROCAM) were calculated essentially by combining the theories of Kimura et al. (2007) and Zhang (2000). Through PROCAM calibration, a transformation matrix of inferred camera and projector could be obtained, which can be used to produce the projected images whose geometry is computed with the ICP algorithm by to the object depth image constructed by an inferred camera. Thereby, the object and projected texture are calibrated.

Cortes et al. (2018) applied the projector-camera calibration method of Yang et al. (2016). Inferred cameras were calibrated with the system (Pintaric and Kaufmann, 2007) to detect the 3D position of reflective markers attached to the objects, which provides the object's geometric information for projection mapping.

4.2.2 Projector-camera Calibration

Even though there are different projector-camera calibration methods, the similarity of these methods is based on the pinhole camera model (Szeliski, 2022), and consider projectors as reversed cameras to formulate intrinsic parameters (representations of optical center and focal length of camera/projector) and extrinsic parameters (representation of the camera/projector location in the 3D scene) (Bimber and Raskar, 2005).

Projector-camera calibration can be conducted with pre-calibrated or uncalibrated cameras (Kourkoulakou, 2020). If pre-calibrated cameras are used, Zhang's method (Zhang, 2000) is the most widely used or adopted camera calibration method. It formulates the camera's intrinsic and extrinsic parameters while the camera captures multiple images of a checkerboard in different random orientations. Then, projector-camera calibration could be done by taking images of arranged projected patterns onto the checkerboard to compute homography from camera coordinates to projector coordinates (Ouellet et al., 2008) (Kurth et al., 2018) (Din et al., 2014) (Liao and Cai, 2008) (Zhang and Huang, 2006) (Moreno and Taubin, 2012). If using uncalibrated cameras, projectors need to project light patterns that can be decoded, such as ARTag markers and structured light, on a flat board. Cameras capture a series of light patterns and use the decoded information to estimate the correspondences between the projector and the camera pixels (Yang et al., 2016) (Fiala, 2005) (Li et al., 2008) (Chen et al., 2009).

4.2.3 Limitations of Existing SAR Geometric Calibration Systems When Applying to the AEC Industry

Firstly, for people from the AEC industry who do not specialize in technical development, the procedures for projector-camera calibration might be too complex. It requires operating a checkerboard multiple times, which is associated with the usage of camera and projector parameters or projecting certain patterns on a panel and then comparing or decoding it by a camera. The whole process consumes an amount of time, and it is even more complicated if the camera needs to pre-calibrate separately. Secondly, there are massive calculations featuring matching algorithms, such as similarity transformation projector-camera calibration, which may slow down the calibration process. Thirdly, conducting two-phase calibration is not direct and simple enough. Fourthly, calibration systems have been developed for the general use of projection mapping for various domains. As BIM represents 3D visualization of the AEC industry, a SAR system that is more compatible with BIM-based design is expected to be developed.

4.3 Methodology

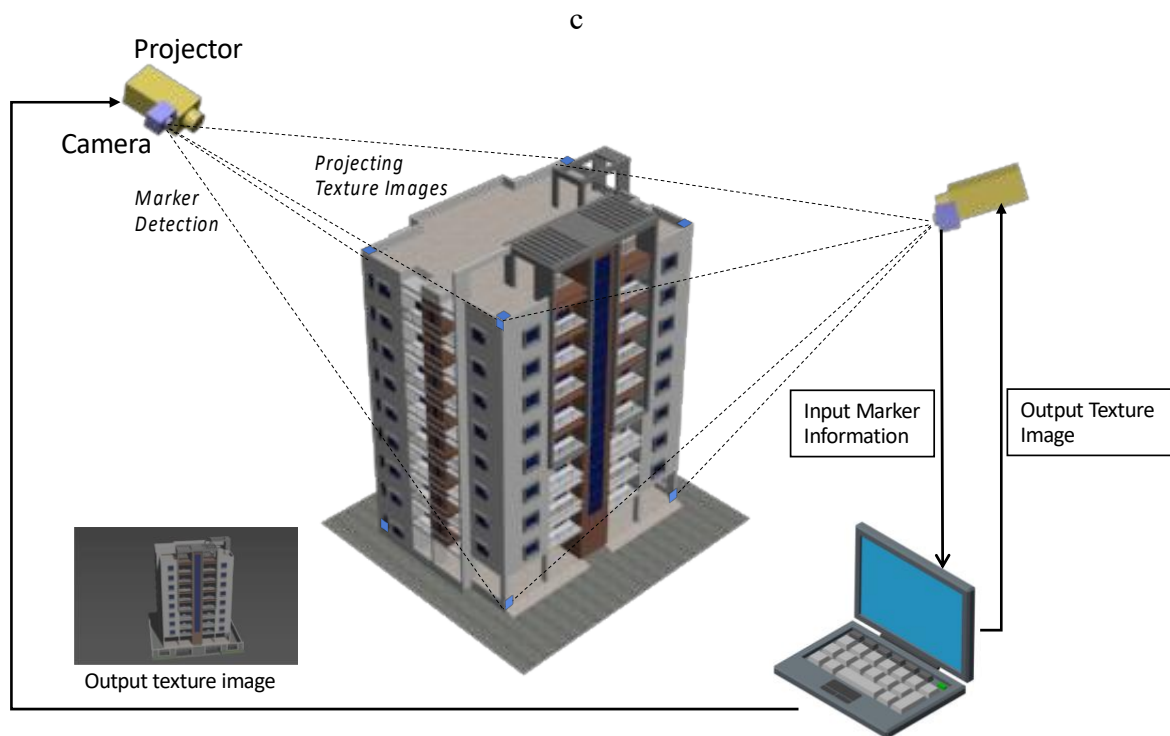


Figure 4-1 System overview

Our SAR system consists of 1) machine vision algorithms, 2) projector-camera pair(s), 3) a target physical model with colored markers attached at reference points, and 4) image extraction from BIM, as depicted in Figure 4-1.

The main idea of the proposed system is to use reference markers to connect a camera, a projector and an object without performing sophisticated calibration procedures for the whole system. A camera detects it to capture geometric information about the physical mock-up model. The relative positions of reference markers on the projection plane can be used to estimate the relative position of the camera and projector, which can eliminate camera calibration processes. Then, image projective transformation allows the creation of projected images that fit reference marker positions.

The global coordinate of reference markers is already known as we have a BIM model. The camera transmits marker information to the processor. Through machine vision algorithms, the position correspondence of markers in the real world and on the projector image frame is estimated. So as to directly build up the correspondence between the model and the projector. In a hardware setting, immobilizing the projectors and cameras where the target physical model is covered by the projector area and markers on the target model surfaces can be fully photted. For geometric calibration, take photos of the model with makers and the projection area when a planar reference panel is placed coincident with a selected surface of the physical model, and the selected surface is the reference surface. The surface covered with the largest projection area is the optimal option. After the only manual procedure of calibration is done, the following calibration and projection can automatically proceed by initially processing the images of markers attached to the model and the projection area. The technical components of the system are illustrated in Figure 4-2, where it follows the flowchart of marker detection, projector-object correspondence and three-point perspective projection correction.

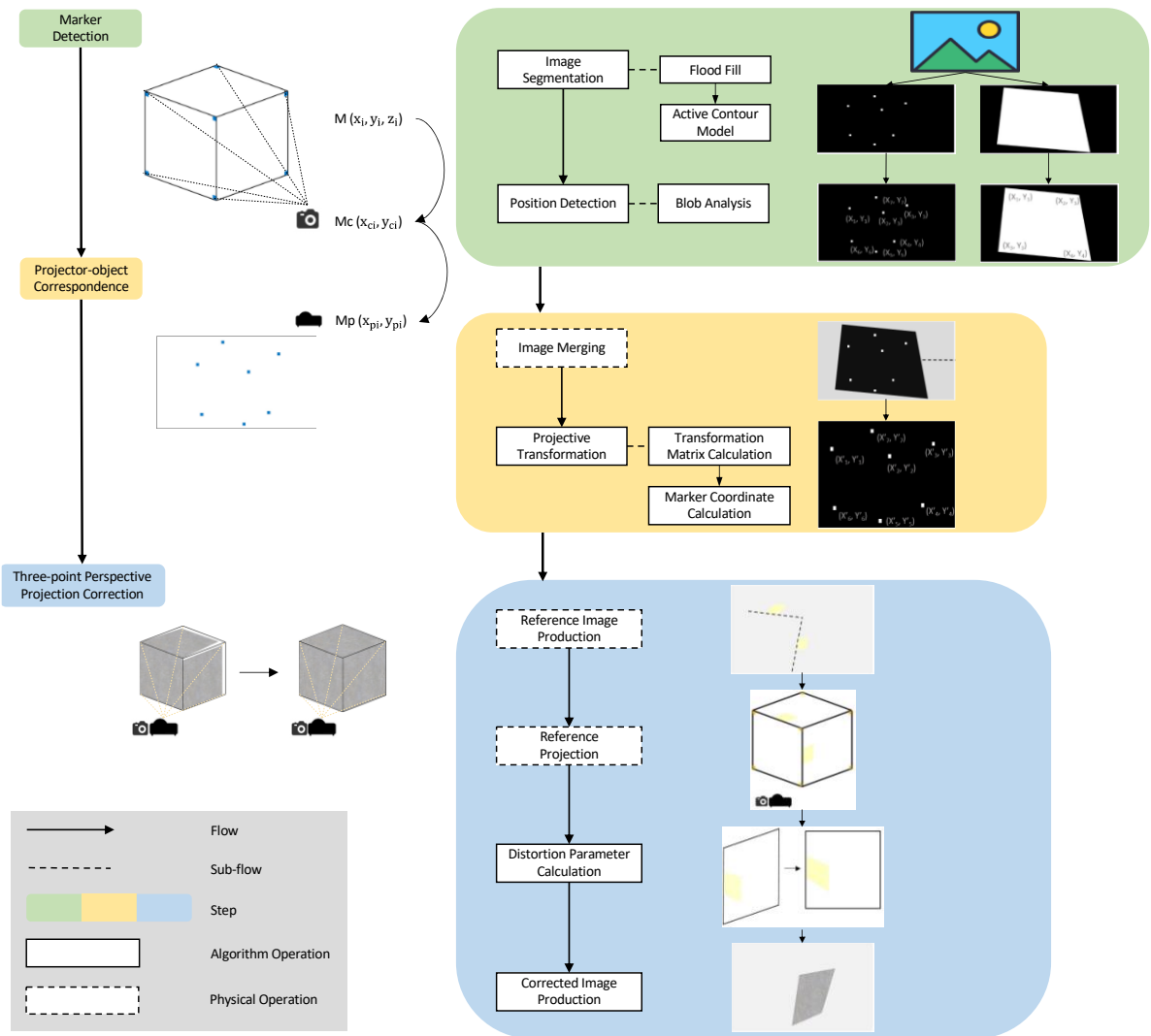


Figure 4-2 System technical structure

4.3.1 Marker Detection

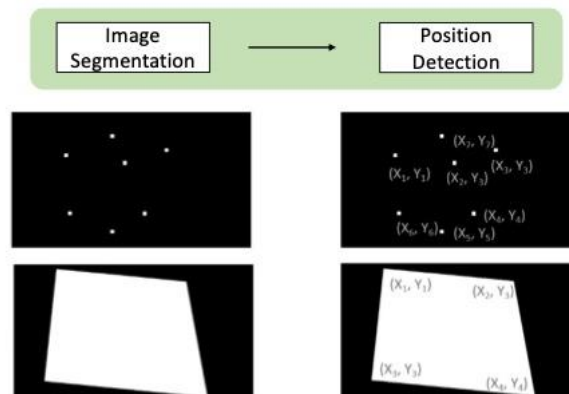


Figure 4-3 Flowchart of Marker Detection

4.3.1.1 Image segmentation

The targeted regions that need to be separated are the projection area and markers, as shown in Figure 4-3. To achieve this, color-based image segmentation methods are chosen due to the highly distinguishable color feature of the projection area and markers compared to the region adjacent to their edge. Moreover, considering it is possible that the color features of few pixels are similar to the projection area and markers on the image background not adjacent to the targeted region, the image segmentation methods process images starting from the selected pixel area are applied. Firstly, we adopt the flood fill method to roughly segment the targeted regions. Then, use the active contours method to refine the segmentation further to marginal pixels.

Flood fill is an automatic technique where you specify starting points and the method segments areas with similar intensity values. It determines and changes the region connected to a given node in a multi-dimensional array with a consistent attribute. The start node, target color, and replacement color are the three essential elements of the flood fill algorithm. The algorithm explores all pixels in the array that are linked to the start node through the route of the target color and then alters them with a replacement color (Adipranata et al., 2015). This research applies queue-linear flood fill (QLFF) as a prompt and highly optimized flood fill algorithm (Dunlap, 2006). This algorithm is implemented essentially relying on two parts. The first sector assembles all required information before calling the second part and transferring it to the coordinates of the start nodes. The second part is to pass the recognized pixels to the furthest reach of the flood fill region along the left and right directions of x axis on the scanline indicated by the y coordinate of image pixels. It fills the pixels it has recognized while checking to the left and right. Then, it adds this horizontal range to a range queue in order to branch up and down and enter a loop of the mentioned two parts. From the second iteration, the algorithm

checks from the left limit passed from the last iteration by one-pixel array along y axis. Each pixel is recognized as the color close enough to the start node, proceeds part two from these pixels, and dequeues the next horizontal range of the queue. Since explored pixels are micro and eligible pixels might not be exactly the same as the start node, the algorithm is designed to recognize the pixels within an adjustable tolerance range. In this research, the tolerance range is represented by value t ($t \in |R|$), which means the tolerance range of deviation is $0 \sim t$. A couple of tolerance ranges are tested to obtain a relatively satisfying outcome for the next step of image processing. An appropriate tolerance range alters the different conditions of camera parameters, background illumination, and shooting angle that will affect the pixel values of images.

Active contour model delineates an object outline from a possibly noisy image. This approach is based on deforming an initial contour C_0 towards the boundary of the object to be detected. The deformation is obtained by trying to minimize a functional design so that its (local) minimum is obtained at the boundary of the object (Kass et al., 1988; Kichenassamy et al., 1996). The formulation proposed by Caselles et al. (1997) is adopted in this research, as shown in the following minimization problem.

$$\min \left\{ E(C) = \int_0^{L(C)} g(|\nabla I_0(C(s))|) ds \right\}$$

Where ds is the Euclidean element of length on each pixel; $L(C)$ is the length of the curve C defined by $L(C) = \int_0^{L(C)} ds$.

The function g is an edge indicator function that vanishes at object boundaries. $g(|\nabla I_o|) = \frac{1}{1+\beta|\nabla I_o|^2}$, Where I_o is the original image, and β is an arbitrary positive constant.

The above functions generally obtain a new length by weighting the Euclidean element of length ds through the function g , which contains information concerning the boundaries of objects. Then, the object boundary is optimized. In this research, curve C is the previous segmentation boundary measured by the marginal pixels. I_0 is the masked image containing the highlighted segmentation area of flood fill and the original image.

4.3.1.2 Position detection

Blob analysis is first used to identify markers and projection areas. A Blob is a group of connected pixels that share some common property. Blob analysis can identify connected regions in grey-scale images. We use the method of filtering blobs by color (Castleman, 1996) (Gupta, 2012). Blob value was set as 1 to select lighter blobs since the color features of markers and projection area are from our image segmentation process. Then, we apply the hough line transform on the identified region to detect the intersections of markers and projection area (Mukhopadhyay and Chaudhuri, 2015). Since we attached a square marker in which one corner is aligned with a target point on the model, the coordinates of intersections of markers that represented the selected corners are used as marker coordinates.

4.3.2 Object-projector Correspondence Estimation

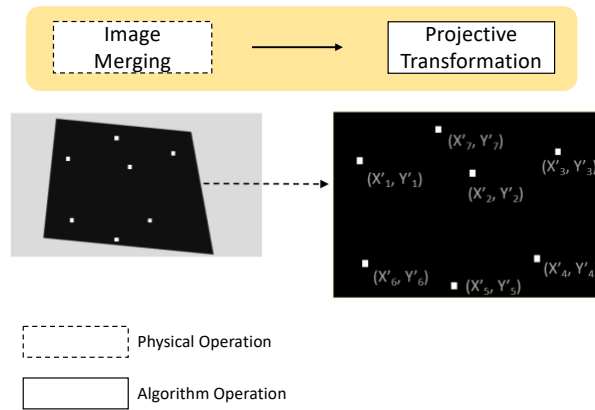


Figure 4-4 Flowchart of object-projector correspondence Estimation

The coordinate information obtained from marker detection is based on the camera frame. To estimate the position of markers on the projector frame, the markers are transformed from the camera coordinate system to the projector coordinate system by applying projective transformation. Projective transformation is a transformation used in projective geometry, which describes what happens to the perceived positions of observed objects when the point of view of the observer changes (Zhang, 2009). Homography represents the correlation between the different points of view. In our case, the correspondence between the object and projector can be established by the homography of markers on a certain observing viewpoint and known projector viewpoint. We have detected certain observing viewpoints as camera-captured images, so building up the transformation from camera-captured images to defined projector frame images is essential to calculate the transformation parameter from the 3D object's geometry mapped to the projector frame.

In projective transformation, coordinates shifted between observers have two kinds of transformations: translation and rotation. Translation refers to location movement, and rotation refers to the camera's angle change. A 3×3 matrix represents the algebraic form of projective

transformation to operate the transformation in a two-dimensional image plane. The transformation matrix could be represented as follows (Andrew, 2001):

$$H = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & 1 \end{bmatrix}$$

Assume that $I_i = (I_{ix}, I_{iy})$ are the coordinates of the points captured by one observer; and $C_i = (C_{ix}, C_{iy})$ are the coordinates of the points captured by the other observer that correspond to points I_i , where $i \in 1, 2 \dots n$. The transformation between these points is formulated as follows (Mantel et al., 2020):

$$\begin{bmatrix} C_{ix} \\ C_{iy} \\ 1 \end{bmatrix} = H \begin{bmatrix} I_{ix} \\ I_{iy} \\ 1 \end{bmatrix}$$

To calculate transformation matrix H , since there are eight degrees of freedom existing in matrix H , at least four-point information needs to be provided for both images. Specifically, the eight corner coordinates of the two images could be pre-set. Then, the whole image transformation can be accomplished by applying projective transformation with matrix H , on every pixel of the original image. The process is illustrated in Figure 4-5.

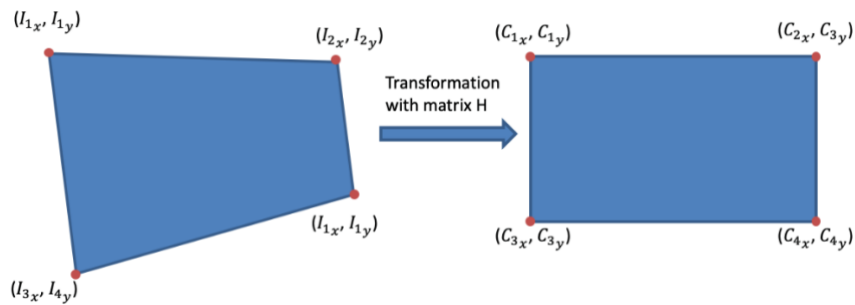


Figure 4-5 Illustration of image projective transformation

4.3.3 Three-point Perspective Projection Correction

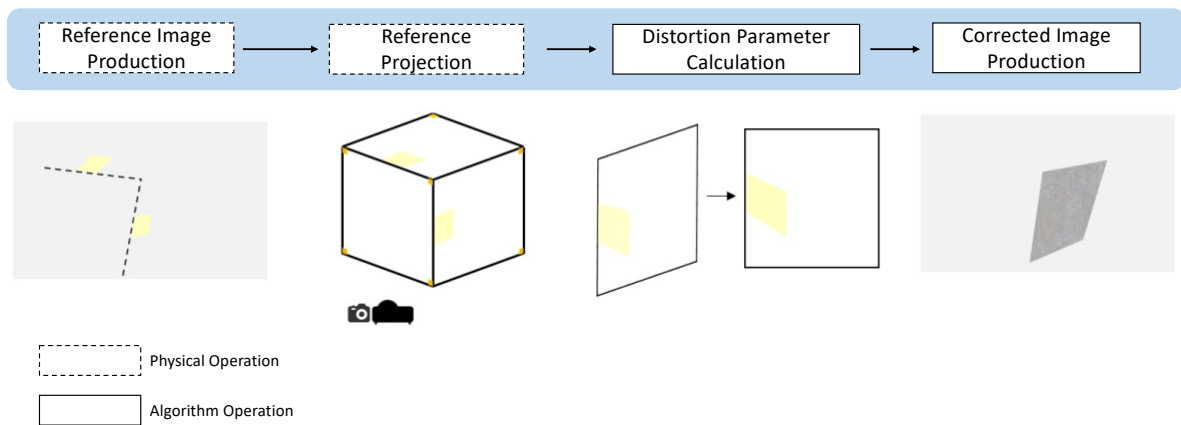


Figure 4-6 Flowchart of three-point perspective projection correction

4.3.3.1 Perspective distortion and three-point perspective projection

Projectors functionalize as reversed cameras. The imaging principle of a camera is based on pinhole model. More specifically, cameras figure unknown points onto a known screen, while projectors project known points of an image into unknown positions (Magnani et al., 2012). It refers to the coordinate relationship between a point on a 3D object in the real world and its projection onto the image plane through a camera. Unless the shooting angle of the camera is fully perpendicularly aligned to the targeted object's surface, the resulting image appears distorted or keystone shape of the object (Foley et al., 1996). Similarly, unless the projector is carefully aligned to the projection surface (screen), the resulting projection on the screen appears keystone.

In addition to perspective distortion, projectors project images on real-world objects following three-point perspective projection (Pastor, 2020) (Yusoff and Zakaria, 2013). Projection of pinhole model also complies with (linear) perspective projection theory. As shown in Figure 4-7, when the image plane is parallel to two axes or the surface of a rectilinear scene in real space, the scene is pictured by one-point perspective projection. By analogy, two-point

perspective projection occurs when the image plane is only parallel to one axis of a rectilinear scene, and if the image plane is not parallel to any axis of a rectilinear scene, it follows three-point perspective projection (Dixon, 1991)

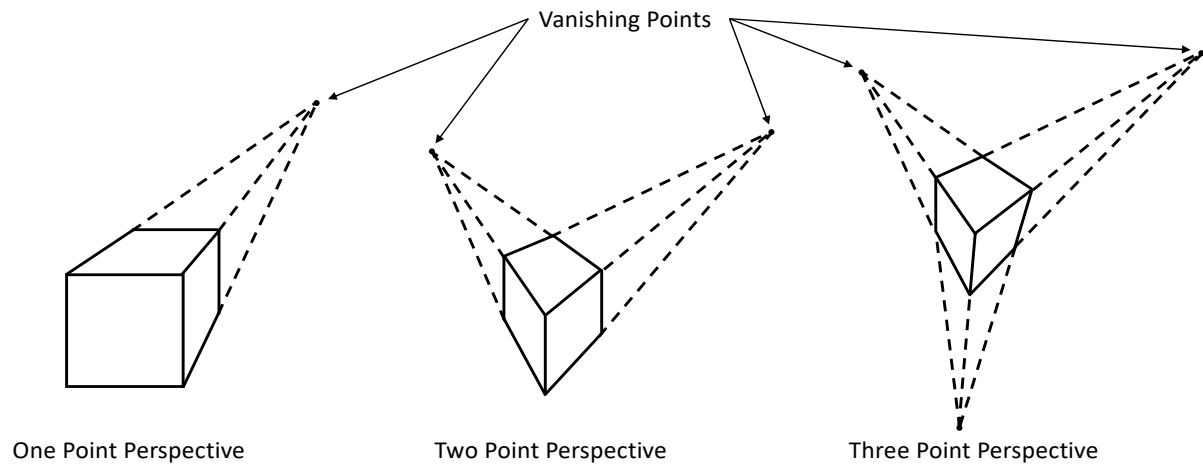


Figure 4-7 Perspective projection diagram

The known projection area captured in an image can solve perspective distortion under the different projector's angles. For one-point perspective projection, all the surfaces share the same perspective distortion. However, surfaces in three-point perspective projection have individual perspective distortion parameters, which means the coordinates of the other surfaces need to be further corrected in terms of the corresponding distortion parameters. In our case, since the reference projection panel is only coincident with one planar of the object, according to the three-point perspective projection model, the projector perspective distortion effect on the other surfaces of the object will not be corrected by exclusively applying the initial input images. To correct the marker positions, the accurate shape and size of the texture images are estimated in terms of the homogeneous projective transformation of the reference projection image and side surface. Precisely, since every planar surface of a 3D object should encounter different perspective distortion effects individually according to the three-point perspective

projection theory, perspective distortion parameter of each surface is needed abstractly to determine the projection shape of the respective surfaces of a 3D object on a uniform 2D image plane. In this study, the perspective distortion effect on a shape boundary is estimated by the transformation matrix T as distortion parameter, where the reference projection image and the boundary of the model surface are transformed together to make the model surface boundary as rectangle. Since the building texture should fill up the model surface boundary, the coordinate correction of texture images on the projector image frame could be defined by an inversive transformation from a certain rectangle texture image with the same transformation matrix T .

4.3.3.2 Projected image generation

For the image on the front surface (surface corresponding to the projection panel), the first step is to transform the shape of the original design images to match the irregular quadrangles formed by linking four detected points. As explained in section 4.3.2, the shape transformation among quadrangles can be processed, where four corner points for each quadrangle are known. 2D images before transformation are the 2D texture images derived from each surface of the 3D BIM model, with the perpendicular viewing angle to surfaces. The resolution of each surface's image picture is measured as $a \times b$ (height $\times$ width); therefore, the coordinates of the image before transformation are $(0, 0)$ $(a, 0)$ (a, b) $(0, b)$ with rotation clockwise from the top left corner. The coordinates of the expected image corners have been detected and calculated previously. A testing sample of building texture is shown in Figure 4-8. Then, put the combined texture image on a white panel, where the panel is the same proportional size as the keystoning corrected image of the projection area. The position of the combined texture image is according to the coordination information of markers with respect to the projection area.

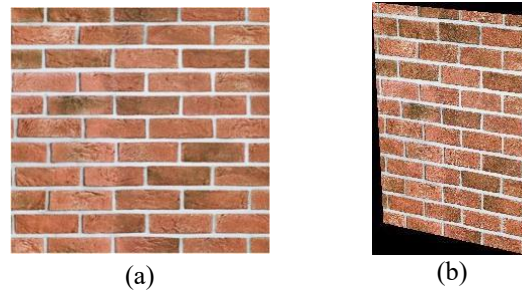


Figure 4-8 Brick texture image. (a) before transformation (b) after transformation

For the images on the side surfaces, the shape and size of the side texture images are defined, and the individual images can be generated in the previous section. Since the location of the front surface image is detected and theoretically correct, putting the side surface images adjacent to the front image can create the whole texture image.

The last procedure is to transfer the image to the same ratio and size as the projection area shown on the projector image frame and to proceed with the projection on the condition of no position changes of projectors and the building model.

4.3.4 Error Estimation

Spatial error of AR estimates the deviation of geometric relationships in the system. Basically, it is the deviation between the location of 3D virtual content expected to be displayed and its actual display in the scene. It could be measured through the 3D location of display devices or the position deviation of virtual contents on the screen (MacIntyre et al., 2002). When the concept is adapted to the spatial error of a SAR system, since the texture image is projected on the surface planes of an object in the physical space, the location deviation could be directly measured from the real-world perspective (Fukiage et al., 2017). In our study, photos captured of the projection can indicate the location where the building model is actually displayed, and the marker positions represent the location where the model is expected to be shown. Moreover, there is a possibility that the model image is projected out of the object boundary into the

surrounding environment when the error occurs, which is unmeasurable by through the object itself. A reference projection panel aids in displaying the entire actual display image in terms of the different surfaces of the object. A projection panel is placed coplanar to the surfaces of the physical model to capture the outcome projection texture of each surface within the respective spatial planar so that the texture can be shown completely on an image plane without spatial twist.

The photos of markers are processed as binary images by image segmentation to clearly show the marker position after merging with the model projection images. Then, the deviation could be measured within the same image frame. The deviation is calculated through the Euclidean distance of feature points. Assume that feature points P_i' are on the image of outcome model projection image captured by camera, and feature points P_i are the points expected to match P_i' . Projection error e of each object's surface can be represented as the mean distance error between P_i' and P_i formulated in (a) (Fukiage et al., 2017). In this study, the value of N is the number of markers on each surface, and the unit of error is pixel. In order to avoid the different viewing angles of the camera with respect to the various surfaces of the object that lead to the incommensurability of error value, kerystoning correction is applied to adjust the image size to the same ratio as the building model. To evaluate the degree of significance of the error, we further calculate the relative error percentage accounts for diagonal dimensions of the projected texture image in pixel level as formula (b)

$$e = \frac{1}{N} \sum_{i=1}^N d(P_i', P_i) \quad (\text{Pixel}) \quad (a)$$

$$e_{\text{Relative}} = \frac{e}{\text{Texture Image Diagonal Dimensions}} \times 100\% \quad (b)$$

4.4 Results and Discussion

4.4.1 Projection Results

According to the methodology proposed, a cube-type building model whose dimension is $85 \times 85 \times 105 \text{ mm}$ was used for sample experimenting. Seven square markers were attached to the corners of the cube's three surfaces, and the position of the projector and camera were fixed during the whole process. The settlement of the physical model, projector, and camera is shown in Figure 4-9.

The sample geometric calibration procedure is demonstrated in Figure 4-10. After marker detection, the projection area displayed in Figure 4-10(e) is a trapezoid. To make it consistent as in the projector image frame, a projective transformation was conducted based on the detected position of the projection area and the known parameter of the projector image frame, that is 1920×1080 according to the projector and projection setting in our study. The transformed binary image is shown in Figure 4-10(f) to detect the marker positions that correspond to the projector frame. Figure 4-10 (g)-(j) demonstrates the detailed process of three-point perspective projection correction.



Figure 4-9 Experiment settlement

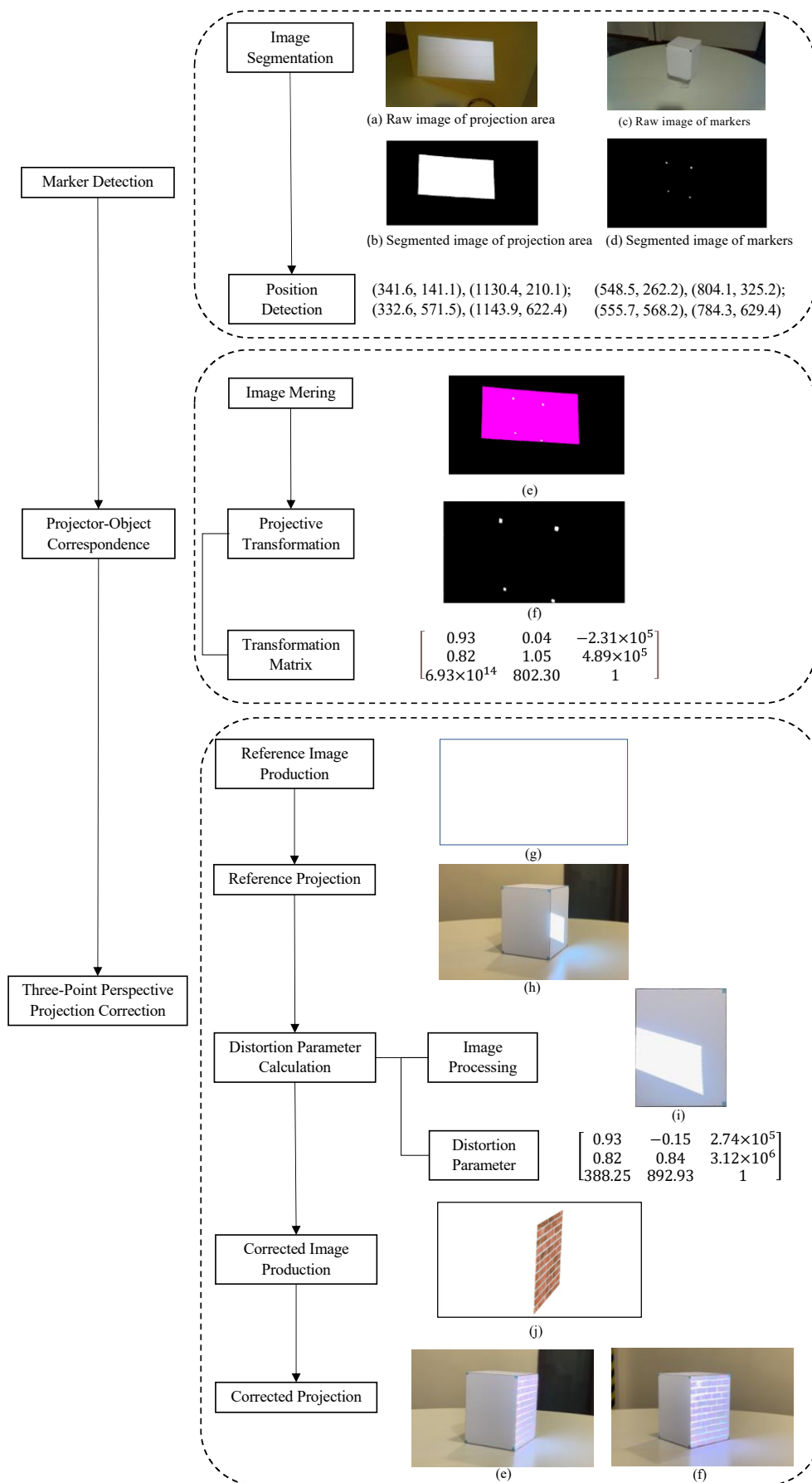
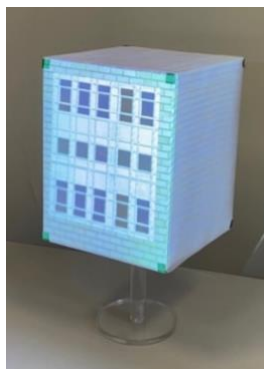
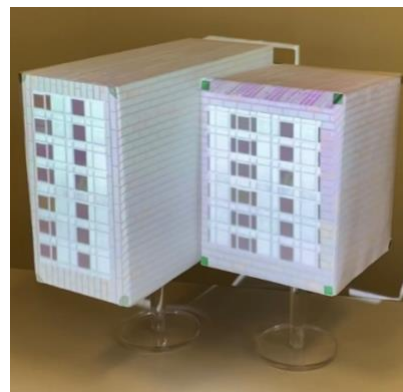


Figure 4-10 Sample geometric calibration flowchart

Projection using the designed texture of the BIM model is shown in Figure 4-11. And testing the compatibility of the proposed method with more complicated building styles. Projection on a multiple-column type model was also conducted, as shown in Figure 4-11(b). The building model was combined by two cubes with the dimensions of $85 \times 85 \times 105 \text{ mm}$ and $65 \times 150 \times 115$. The adjacent surfaces of the two models form in-line special corners, which triggers the difficulty of solving the perspective distortion issue of different special planar, and there is no space for showing the whole projection area on the corner building surfaces. However, the method of this study can constantly implement perspective distortion correction if only there is a non-keystoned projection on one adjacent surface. In other words, the physical reference panel only needs to be placed once the whole projection and correction process can be automatically operated by the computer algorithm without manual operation. After having the distortion parameters of different planar surfaces on the model, the actual positions of all the feature points on the model could be estimated to generate the projection image by inputting the separately designed texture of the BIM model.



(a)



(b)

Figure 4-11 Projection with designed BIM model texture. (a) Single volume model; (b) Multiple volume model

4.4.2 Error Estimation and Discussion

This study estimated the geometric calibration errors of the two above models. To indicate the related error values, the surfaces of models were named Figure 4-12, and surface 1 is the reference surface to show the projection area for both models. Figure 4-13 shows an example of estimating the Euclidean distance of feature points by comparing the projected texture on the reference panel with the position of the physical model represented by markers. Table 4-1 presents information on error estimation. Corner points where attaching markers were selected as feature points, so d is the Euclidean distance between the feature point on the projected image and the model. The projection error on three surfaces of the single-volume model and on six surfaces of the multiple-volume model were estimated. Also, to explore the effect of projector-camera pair position relation with models on the projection accuracy, position conditions that projector-camera pair that is more perpendicular and more horizontal tilted to the front surface of the model were considered as set in Figure 4-13 (b).

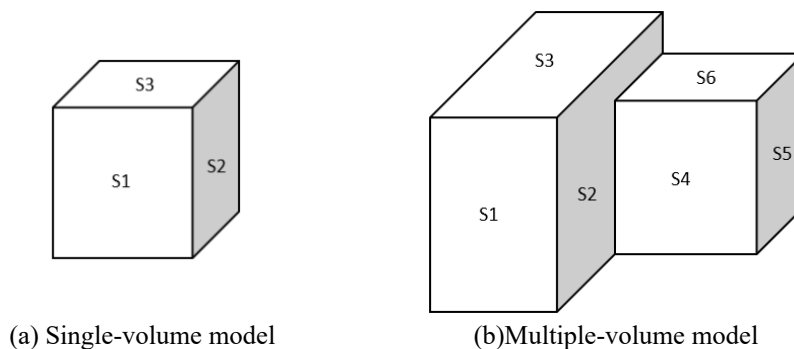


Figure 4-12 Model graphical representation for error estimation

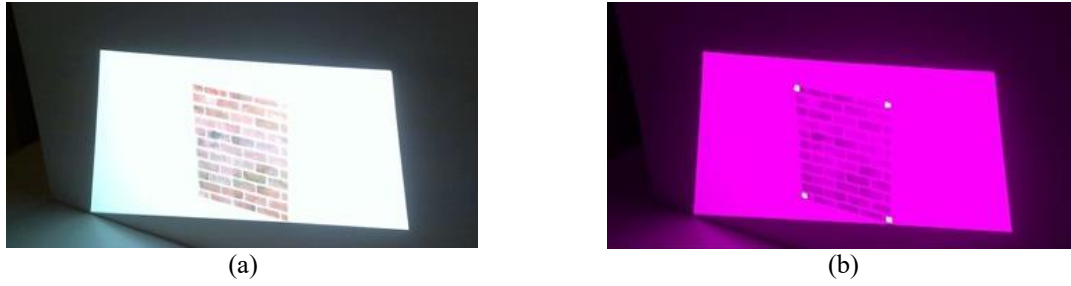


Figure 4-13 Image projection on the reference planar compared with
(a) actual projection and (b) marker position

Table 4-1 Information of Error Estimation

		Projector-camera pair more perpendicular		Projector-camera pair more horizontally tilted	
Models	Surfaces	D (pixel)	$e_{Relative}$ (%)	D (pixel)	$e_{Relative}$ (%)
Single-Volume Model	1	4.37	0.97	5.58	1.47
	2	4.92	1.19	6.63	1.84
	3	5.39	1.75	6.25	1.98
	Overall	4.90	1.21	6.03	1.48
Multiple-Volume Model	1	3.78	0.94	5.36	1.33
	2	4.49	0.98	6.96	1.52
	3	5.62	1.18	6.63	1.40
	4	5.53	1.23	7.13	1.59
	5	6.71	1.62	8.53	2.05
	6	7.08	1.94	7.57	2.07
	Overall	5.53	1.31	7.03	1.66

As seen from Table 4-1, the results of the overall errors of the two models suggest that the projection accuracy is good. The overall errors are from 4.90 to 7.03 in the pixel level, and the relative errors in terms of the whole texture images ranged from 1.21% to 1.66%, which could be considered a small error. And projection is more accurate when the projector-camera pair is more perpendicular to the front surface. Since the front surface is selected as the reference surface to display the projection area in our case, it can be said that setting the projector-camera pair more perpendicular to the reference surface helps to improve projection accuracy.

From the perspective of errors on the individual surfaces, it can be derived from the data that projection on surface 1 of both models is the most precise. The surfaces adjacent to surface 1 have fewer errors. It might indicate that even though our calibration system deals with the three-point perspective distortion issue, the error still occurred during the distortion correction process. Considering the errors on the surfaces and overall error are small, the error of three-point perspective projection correction is also small and acceptable.

4.5 Conclusion

Spatial Augmented Reality has been used in various fields for design visualization. Geometric calibration, a key component of SAR, projects designed textures onto 3D objects. Many calibration systems exist, but for simpler applications in building design, a user-friendly automated system was developed. This system uses machine vision algorithms with an uncalibrated projector-camera pair to find the position of markers, linking the projector and the physical model. The accuracy of this system has been validated with different building models and projector-camera placements, showing minimal error. This system is advantageous because it doesn't need projector-camera calibration and integrates the entire calibration process. The only manual step is placing a white panel on the model surface and taking a picture, making it easy for AEC professionals. It also allows direct input of BIM model textures for better BIM appearance design. Nevertheless, our system has only been tested on the building models constituting planar surfaces. Curve surfaces are expected to be tested for more comprehensive applications on various types of buildings. Since curve surfaces may result in more complex perspective projection when projecting images into 3D space, and the perspective distortion would be inconsistent on the same curve surface, further calculation methods need to be explored to estimate the distortion parameters. Moreover, we only applied one PROCAM pair to demonstrate the feasibility of our system. If another PROCAM pair

projects the other sides of the model, there will be overlapping projection areas where one more layer of projection light is unbelonging to the texture image.

Chapter 5 Spatial Augmented Reality (SAR)-based Daylight Simulation and Visualization for Building Exterior Design

5.1 Background

Daylight plays a crucial role in the design of buildings, as it can significantly impact energy efficiency, occupant comfort, and overall aesthetic (Lehar and Glicksman, 2007). Daylight simulation provides performance measures that support design decisions, allowing architects to assess the impact of daylighting strategies on various design aspects (Reinhart & Fitz, 2006). For example, daylight analysis through simulation can support the design decision process for shading type, window size, glazing type, lighting controls, building orientation, or surface properties. Also, it can help to investigate user preferences, photometric data, visual effects, and energy considerations by visualizing, quantifying, and assessing building performance under various environmental conditions (Nazari and Matusiak, 2024) (QuillBot, 2024).

There are various daylight simulation tools available for building design, such as 3ds Max, Lightwave and Blender (Jakica, 2018). Through the integration of BIM with these simulation tools, architects and engineers can now leverage the power of digital modeling to explore the interplay between a building's design, orientation, and the behavior of natural light. Especially the use of mixed reality (MR) technology, for example, immersive virtual reality (IVR) or augmented reality (AR), as a visualization medium for daylight simulations is gaining attention in architectural design as it can provide immersive experience to users for building design affected by daylight. One of the essential benefits of mixed reality technology in building daylight simulation is the ability to interpret brightness and color variations in a manner that closely mimics the human eye (Nasman & Cutler, 2013). This enhanced level of visual fidelity enables design professionals to make more informed decisions about the placement of building components, the use of shading devices, and the overall integration of natural lighting within the built environment (Ko et al., 2021). Moreover, virtual reality can facilitate collaborative

design processes, enabling stakeholders to collectively evaluate and refine daylight strategies, leading to more informed and effective design decisions (Reinhart & Fitz, 2006).

5.2 Daylight Simulation

5.2.1 Building Information Modelling on Daylight Simulation

BIM technology offers a visually and dimensionally accurate three-dimensional digital representation of a building, along with a database of data attributes for its components (Sabol, 2013). The integration of Building Information Modeling (BIM) into architectural design has revolutionized the way professionals approach the built environment, providing a comprehensive digital representation of a structure that encompasses various facets, including the simulation of sunlight exposure (Jang and Lee, 2023). As daylighting plays a crucial role in the occupant comfort and energy efficiency of buildings, researchers have dedicated considerable efforts to exploring the potential of BIM-based sunlight simulation techniques (Le-Thanh et al., 2021) (Gao et al., 2017) (QuillBot, 2024).

Also, the integration of sunlight simulation within BIM models allows architects and engineers to analyze and optimize the building's performance in a more comprehensive manner. By incorporating detailed sunlight simulation capabilities, they can assess the impact of natural lighting on critical factors such as the building's energy consumption, the quality and distribution of daylight within the interior spaces, and the movement and comfort experienced by the occupants as they navigate the space. This holistic analysis enables the design team to make more informed decisions and refine the building's design to enhance occupant well-being and overall sustainability (Menges et al., 2017).

One key aspect of daylighting analysis is the assessment of daylight availability, which can be achieved through the application of various simulation software tools (Ahmad et al., 2020). These tools can predict daylight illuminance and even its consequences on energy consumption, enabling the selection of optimal building designs. Recent research has highlighted the advantages of utilizing BIM-based daylight simulation tools in the design process, particularly in hot, arid climates where effective daylighting can lead to significant energy savings and enhance occupant comfort and well-being (Saraf and Bhavani, 2017) (Garcia et al., 2018). These tools have the ability to generate analytical models in an automated or semi-automated way, streamlining the simulation process and reducing the potential for errors. One such tool, Insight, a daylighting analysis plugin for Revit, provides daylight performance assessments to non-specialist professionals and allows them to conduct daylighting analyses directly within the BIM environment. This accessibility and ease of use have the potential to streamline the design process and reduce the time and cost associated with traditional simulation workflows (Garcia et al., 2018).

Despite the availability of these simplified and detailed daylight simulation methods, research suggests their adoption in building design has been limited. (Reinhart & Fitz, 2006) A web-based survey conducted within the context of the International Energy Agency identified weaknesses of existing daylighting design software and a better understanding of the needs of design practitioners (Welle et al., 2012). The survey findings provided insights that the continued development and refinement of tools, coupled with a deeper understanding of design practitioners' needs, will be crucial in driving the widespread adoption of BIM-centric daylight simulation practices in the building industry. Such developments are also suggested to offer a promising approach to automate the identification of building spaces for daylighting analysis to simulate spatial results. Also, systems that automate and spatialize the critical components

of daylight simulation systems can significantly streamline the daylighting assessment process, enabling designers to explore a wider range of design alternatives and ultimately optimize the building's occupant comfort and overall performance.

5.2.2 Mixed Reality Technology for Daylight Simulation

As the built environment continues to evolve, the need for effective and efficient daylight simulation has become increasingly important. (Scorpio et al., 2020) Mixed reality technology has emerged as a promising tool for this purpose, offering a comprehensive and immersive approach to evaluating and optimizing daylight performance in buildings.

Existing research highlighted the limitations of traditional daylight simulation methods observing the outcomes on the computer screen, particularly in their inability to adequately capture the dynamic and complex nature of daylight (Reinhart & Fitz, 2006). These conventional tools frequently struggle to replicate the dynamic and nuanced nature of natural lighting, limiting the ability of designers and stakeholders to fully visualize and appreciate the impact of daylight on the built environment. Moreover, conventional computer-based tools often fail to provide an engaging experience for design professionals and end-users.

However, the development of mixed reality technology has opened new avenues for daylight simulation. VR-based systems such as RadVR simulate light behavior and optical performance, offering a more immersive and interactive platform for evaluating daylight performance (Keshavarzi et al., 2021). Moreover, some systems integrate geometric location and sun-path tracking features within these virtual environments, coupled with the utilization of Building Information Modeling (BIM), which has enabled the development of daylight-responsive models that can optimize the usage of natural lighting and minimize energy consumption for

artificial lighting (Sait et al., 2019). These innovative approaches not only benefit the design process but also empower architects, engineers, and other stakeholders to collaborate and virtually visualize the lighting conditions in a virtual environment, ultimately leading to more informed and efficient design decisions.

A key advantage of using mixed reality for daylight simulation is its ability to accurately depict the visual effects of daylight, allowing designers and researchers to assess the impact of design decisions on the occupant experience (Saraf and Bhavani, 2017). By immersing users in a virtual environment, they can directly observe and interact with the daylight conditions, gaining a deeper understanding of how lighting affects the overall ambiance and functionality of a space. Moreover, virtual reality can facilitate collaborative design processes, enabling stakeholders to collectively evaluate and refine daylight strategies, leading to more informed and effective design decisions (Reinhart & Fitz, 2006). By incorporating virtual and augmented reality elements, designers can manipulate building forms, materials, and fenestration systems to optimize daylight performance and ensure occupant comfort and well-being. Furthermore, the integration of mixed reality technology into daylight simulation can further enhance the design process by providing immersive, interactive experiences that allow designers to visualize and assess the daylighting conditions in real time (Sharp et al., 2014). Ideally, the automated identification of building spaces for daylighting analysis, the simulation of spatial results, and the scaling of spatial simulation results to whole building performance metrics might significantly streamline the design process and reduce the time required for daylighting assessment (Welle et al., 2012). The use of this technology can enable designers and researchers to create built environments that are not only visually appealing but also enhance the user experience and promote sustainability by providing a more immersive and engaging approach to daylight evaluation.

5.2.3 SAR for Daylight Simulation

From a technical perspective, existing AR systems that use a tablet or head-mounted display require real-time tracking technology that relies on sensor detection to enable precise and effective registration while users are in motion. Within this framework, sensor errors may easily occur (Mekni and Lemieux, 2014). Furthermore, users may feel discomfort caused by holding a tablet or wearing a heavy head-mounted device (Park and Moon, 2013). As existing AR users see an augmented view through their own AR displays, it is difficult to build common reference points between users when representing spatially-located virtual data, which as a result, hinders the common understanding of virtual information compared with a shared physical space (O'Hare et al., 2020; Wang, 2009). The quality of visualized information is still low due to the technical limitations of existing AR devices. For example, while using a head-mounted AR display (e.g., Microsoft HoloLens), low resolution, distortion, and limited field of view could lead to a false perception of visualized information. Brightness, contrast, and visibility are other screen-related issues that can significantly affect visualization quality (Kruijff et al., 2010).

Unlike traditional mixed reality, which overlays digital content onto the user's view of the physical world, SAR projects digital content directly onto physical surfaces, creating a seamless blending of the real and virtual environments. It enables designers and engineers to seamlessly integrate digital content with physical spaces, creating immersive and dynamic experiences. Compared to IVR and AR, SAR allows users to interact with virtual content overlaid directly onto the physical world around them (Lee, Sedlmair and Schmalstieg, 2023). This provides a more seamless and intuitive experience, as users can naturally engage with digital information in the context of their physical surroundings (Safi, Chung and Pradhan, 2019). Furthermore, spatial AR offers enhanced spatial perception and data visualization

capabilities compared to traditional AR. Several visual cues, such as depth cues and object occlusion, can be leveraged in spatial AR to better convey the three-dimensional relationships between virtual content and the physical environment (Luboschik et al., 2016). This can be particularly beneficial for applications involving complex 3D data visualization, where the ability to spatially reason about data is crucial (Bimber and Raskar, 2005).

Therefore, SAR could offer several advantages over other mixed reality technologies in daylight simulation of building projects. Firstly, SAR can provide a more immersive and natural interaction of daylight by projecting adjustable color and intensity of the light beam, which could be highly similar to natural daylight. Additionally, SAR does not require the user to wear any specialized hardware, such as head-mounted displays, allowing for a more social and collaborative experience in observing the daylight simulation. Moreover, users can directly manipulate physical building models to gain different outcomes from daylight effects on variable physical model angles and positions, which benefits design decision-making.

5.3 Methodology

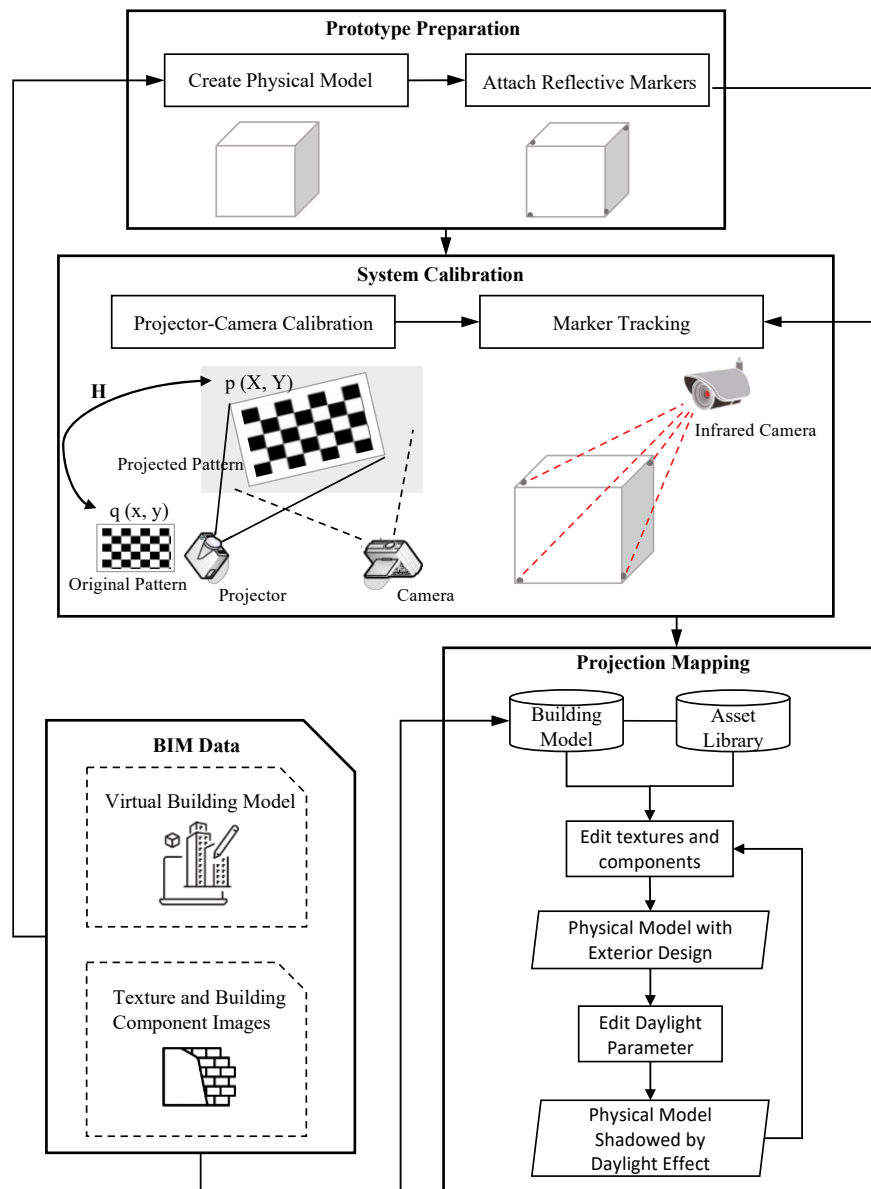


Figure 5-1 Flowchart of SAR-based Daylight Simulation System

Figure 5-1 describes the process for simulating daylight effects on a physical building model using a projector-camera system and reflective markers. The process begins with assembling a small-scale physical model of the building, onto which a series of reflective markers are attached for tracking. Once the model is ready, the next step is calibration: both the projector and the overhead camera are carefully aligned so that every marker can be reliably followed in three-dimensional space. During this calibration phase, a reference pattern is displayed on the

model and recorded by the camera, establishing a tight correspondence between the real-world object and its digital twin. After achieving this spatial accuracy, BIM data is imported to generate a fully realized virtual rendition of the building, enriched with textures and imagery pulled from an existing asset library. Using projection mapping software, these newly imported digital components are mapped onto the surface of the physical model, allowing designers to visualize alterations to its façade in real time. To round out the presentation, the system's daylight parameters are fine-tuned, producing dynamic shadows and color temperatures that mimic sunlight. The result is a seamless blend of virtual and tangible elements that provides architects with an intuitive preview of design performance under natural light.

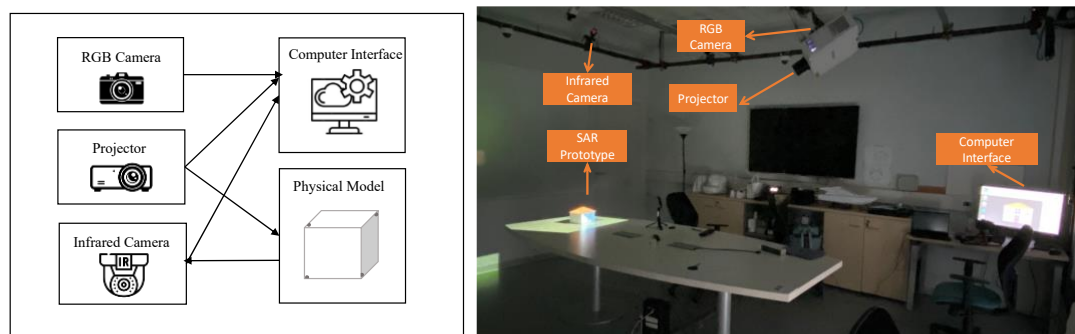


Figure 5-2 System Equipment Setup

Figure 5-2 shows the components of the proposed SAR-based Daylight Simulation System. The SAR platform developed could be operated in the computer interface to insert virtual building models, edit textures and building components and adjust daylight simulation parameters. RGB camera is used for projector-camera calibration, and an infrared camera is used to track the spatial location of the prototype.

5.3.1 SAR Platform Selection for Daylight Simulation Plugin

There are different projection mapping platforms available. To have potentials of the development of building daylight simulation system, the following basic requirements of projection mapping platforms should be considered.

- (1) Ability to precisely map on the 3D object. Some of the projection mapping platforms only allows 2D surface calibration. Nevertheless, both projecting 3D building virtual models and simulated daylight required spatial calibration to display on 3D physical building models.
- (2) Automatic geometric calibration. The automated calibration procedures eliminate the need for time-consuming and potentially error-prone manual adjustments, freeing up time and resources of the whole simulation process.
- (3) Tracking function. Tracking function could provide real-time projection movable physical building models to generate the different daylight effects on varying position and angles of the physical model.
- (4) Interaction function. Platform to have the texture editing possibility on virtual models, enabling real-time design of building components according to daylight effects.

5.3.2 Introduction of SPARK Platform

The SPARK platform is described as a responsive and intuitive ICT tool that utilizes Spatial Augmented Reality to enhance collaboration between designers and stakeholders, such as clients and end-users, during the ideation process (Morosi et al., 2023). It is particularly valuable in the fields of product interface and packaging design. The platform aims to foster the development of new ideas by providing a collaborative environment where designers and stakeholders can interact and contribute their perspectives. The use of SAR technology suggests that the platform incorporates virtual elements into the real-world environment, allowing users to visualize and manipulate design concepts in a more immersive manner.

The SPARK platform acts as the interface between the users and the virtual prototype, enabling them to collaborate and make design decisions (Garcia et al., 2017). It is responsible for several key functions related to the virtual prototype and user interaction (Morosi et al., 2018): 1) Interaction Handling: It manages how users interact with the virtual prototype during co-design sessions. This could involve manipulating the prototype, providing input, and receiving feedback. 2) Visual Display: It likely handles the visual representation of the virtual prototype, allowing users to see and understand the design in a digital format. 3) Session Preparation: The SAR module plays a role in setting up and preparing the virtual environment for co-designing sessions. This might involve loading the prototype, configuring tools, and establishing communication with other modules. Figure 5-3 shows the usage of SPARK on industrial design.

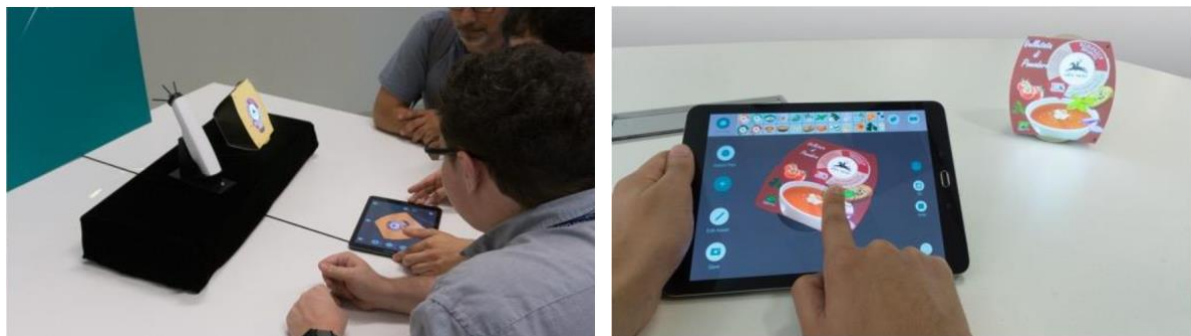


Figure 5-3 SPARK for Industrial Design

Calibration of SPARK

SPARK platform applies projector-camera calibration method (Moreno and Taubin, 2012). A local homography is computed for each corner of the checkerboard by taking into account all the accurately decoded points within a region of the camera picture that is centered around the corner's location. Let p be the pixel coordinates of a location in the patch being examined, and

let q represent the decoded projector pixel for that point. We may then determine a homography H that minimizes the following:

$$H = \min \sum \|q - Hp\|^2$$

$$H \in R^{3 \times 3}, \quad p = [x, y, 1]^T, \quad q = [col, row, 1]^T$$

The target corner $\bar{p}$ at the center of the image patch is converted to $\bar{q}$ in projector coordinates using the local homography H :

$$\bar{q} = H \cdot \bar{p}$$

The identical approach is reiterated until all corners of the checkerboard have been translated. Now, with the knowledge of the precise positions of all corners in the projector coordinate system, the calibration of the projector's internal properties is determined using the same technique as for the camera.

A connection between the pixels of a projector and a camera could be established, which is derived from structured-light sequences. And this connection is to determine the positions of checkerboard corners in projector pixel coordinates. Furthermore, by performing all calculations at the camera's original resolution, the corner coordinates can be localized with higher accuracy compared to using synthetic images at the projector's resolution.

The process of calculating the coordinates of checkerboard corners in the projector coordinate system can be broken down into three steps. Firstly, the structured-light sequence is decoded and each camera pixel is assigned a projector row and column, or marked as "uncertain". Secondly, a local homograph is determined for each checkerboard corner in the camera image. Finally, each corner is transformed from camera coordinates to projector coordinates using the

previously calculated local homograph as illustrated in Figure 5-4. The positions of the projector corners are determined with sub-pixel accuracy by employing local homographs for each corner in the camera picture.

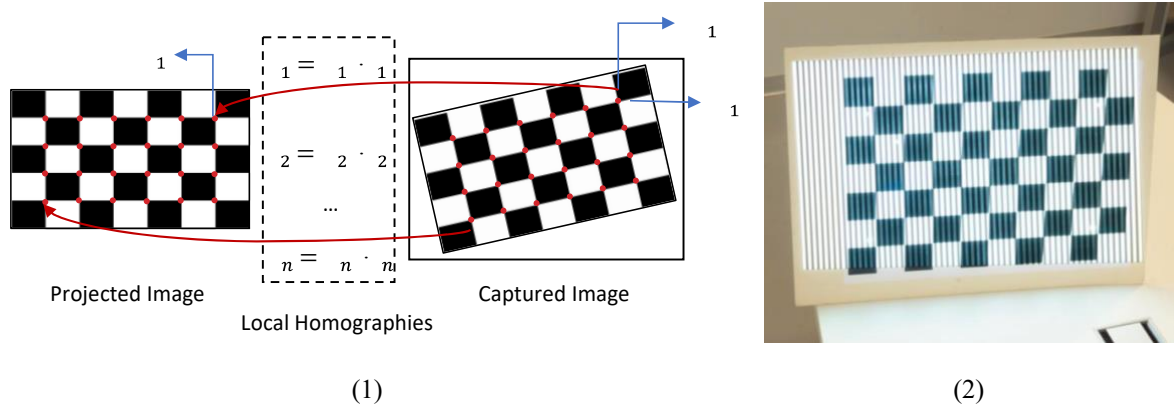


Figure 5-4 Using local homographies to estimate projected corner locations to each corner in the camera image. (1) Conceptual graphic (2) Calibration process during structural light pattern projection

The calibration of projectors in the SPARK platform is achieved by utilizing conventional RGB cameras (webcams) that are securely attached to the external case of the projectors in a fixed location. This task is mandatory for every projector and should only be repeated if there are any alterations to the projector cone.

The algorithm utilized is founded on structured light and enables the extraction of both the intrinsic and extrinsic parameters of the projector. This technique employs an automated process to display and record a series of designs, the quantity of which is determined by the quality of the projector, onto a pre-existing checkerboard. A minimum of three sets of photos is required to provide results with adequate precision. It is crucial to rotate the chessboard in each of the three sets, considering the following factors: ensuring that the projected image fully covers the printed target, enabling the camera to easily detect the corner of the target, and adjusting the camera settings to capture both high and low brightness conditions.

5.3.3 Daylight Simulation Algorithm and Plugin Development

Solar position is used to simulate the solar light source in relation to the building at different times and locations. The solar position is typically defined by two angular coordinates: the solar zenith angle and the solar azimuth angle. The solar zenith angle represents the angle between the sun's rays and the vertical at a given location, while the solar azimuth angle describes the sun's relative direction along the local horizon. (Zhang et al., 2021). Solar zenith angle and the solar azimuth angle could be calculated by basic parameters of latitude, longitude, time zone, year, month, day, hour, minute and second. Therefore, we developed an interface by using the solar position algorithm that can easily input and adjust these basic parameters to simulate the daylight in regard to specific locations and times in the earth.

5.3.3.1 Solar Position Calculations

Solar position is calculated to simulate the spatial relationship between solar beam and the building model. In VR software, the daylight effect of the whole scene is rendered to show on the screen. In the proposed SAR simulation system, the projector does not act as the light source of solar beam, but project the rendering outcome on the physical environment. Therefore, the projector is fixed that to keep the system convenient and stable. The comparison between VR daylight simulation and SAR daylight simulation is shown in Figure 5-5.

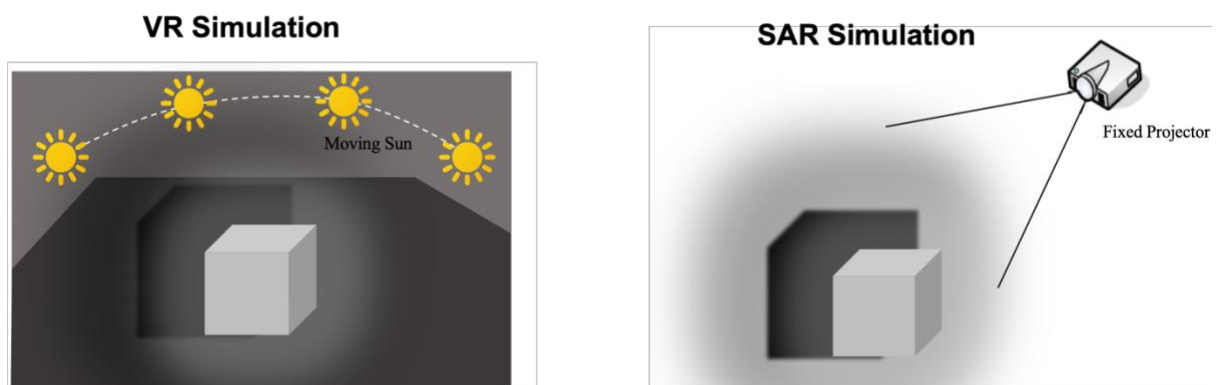


Figure 5-5 Comparison of daylight simulation between VR and SAR

The solar position algorithm is used from Reda and Andreas (2004). First, the fractional year (γ) is calculated, in radians.

$$\gamma = \frac{2\pi}{365} \times \left(\text{day of year} - 1 + \frac{\text{hour} - 12}{24} \right)$$

(For leap years, use 366 instead of 365 in the denominator.)

From γ , we can estimate the equation of time (in minutes) and the solar declination angle (in radians).

$$\begin{aligned} eqtime = & 229.18 \times (0.000075 + 0.001868 \cos \gamma - 0.32077 \sin \gamma - 0.014615 \cos 2\gamma \\ & - 0.040849 \sin 2\gamma) \end{aligned}$$

$$\begin{aligned} decl = & 0.006918 - 0.399912 \cos \gamma + 0.070257 \sin \gamma - 0.006758 \cos 2\gamma \\ & + 0.00907 \sin 2\gamma - 0.002697 \cos 3\gamma + 0.00148 \sin 3\gamma \end{aligned}$$

Next, the true solar time is calculated in the following two equations. First the time offset is found, in minutes, and then the true solar time, in minutes.

$$time\ offset = eqtime + 4 \times longitude - 60 \times timezone$$

where $eqtime$ is in minutes, $longitude$ is in degrees (positive to the east of the Prime Meridian), $timezone$ is in hours from UTC (U.S. Mountain Standard Time = -7 hours)

$$tst = hr \times 60 + mn + sc \div 60 + time\ offset$$

where hr is the hour (0 - 23), mn is the minute (0 - 59), sc is the second (0 - 59)

The solar hour angle (ha), in degrees, is:

$$ha = (tst \div 4) - 180$$

The solar solar zenith angle ($\emptyset$) can then be found from the hour angle (ha), latitude (lat) and solar declination ($decl$) using the following equation:

$$\cos \emptyset = \sin(lat) \sin(decl) + \cos(lat) \cos(decl) \cos(ha)$$

And the solar azimuth (θ , degrees clockwise from north) is found from:

$$\cos(180 - \theta) = -\frac{\sin(lat) - \cos(\emptyset) - \sin(decl)}{\cos(lat) \sin(\emptyset)}$$

5.3.3.2 Plugin Development

SPARK platform was developed based on Unity. The versatility of Unity can be attributed to its robust graphics design and visualization capabilities, as well as its ease of integration with external systems (Wang et al., 2020). This has made it a valuable tool for researchers and developers working in diverse fields, from augmented reality game development (Kim et al., 2014) to virtual reality-based training systems (Xiong, 2022).

One of the basic tools of Unity is to generate light simulation of the scene by putting transform parameter position (x,y,z), rotation (x,y,z) and scale(x,y,z). Since sunlight as a directional light, whose light exposure on earth is not be influence by position(x,y,z) , and scale(x,y,z) is defined as 1, the parameters rotation (x,y,z) are required to be put to generate the sunlight simulation.

Solar zenith angle ($\emptyset$) represents rotation (x,1,1), solar azimuth (θ) represents rotation (1,y,1), and rotation (1,1,z) is static as 1. As states in the solar position calculations, there are original input parameters of latitude, longitude, time zone, year, month, day, hour, minute and second to calculate the solar zenith angle and solar azimuth.

Then, the plugin interface was design as adjustable toolbar, by using C# computer language. As show in Figure 5-6, we add 'Edit Light' function in SPARK platform for daylight simulation.

After inserting virtual building model, building texture and component images to SPARK platform, the model appearance could be edit on the interface. There are nine toolbars detailly when selecting Edit Light function, and the toolbars can be dragged to change the values of corresponding parameters.

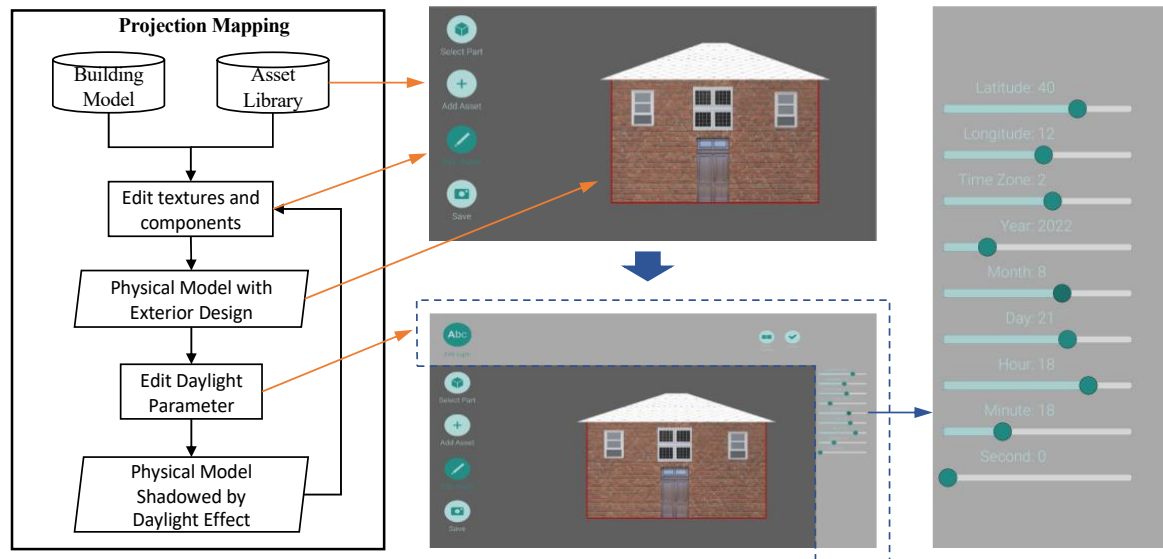


Figure 5-6 Development of daylight simulation interface

5.4 Application Procedures

5.4.1 Prototype Preparation

The physical prototype is a tangible model that represents the previously created 3D virtual building model. It should accurately reflect the virtual model's shape and can be constructed using various techniques and materials. However, objects with soft or deformable shapes are not compatible with the SPARK platform. The prototype can be created using methods like 3D printing or traditional prototyping techniques, starting with the 3D model file. To ensure optimal visualization during projection, the prototype's exterior should be painted matte white, and its surface should be as smooth as possible to prevent visible defects and enhance the projected images' clarity.

This physical prototype, combined with the projected visuals, forms what is known as the projected model. During design sessions, participants can interact with this projected model, and the projected view will move accordingly based on the tracking system. To enable tracking, the prototype must be equipped with spherical or hemispherical reflective markers, as illustrated in Figure 5-7. At least four markers need to be placed to track the prototype spatially. These markers can be placed on the prototype's most visible surfaces, ensuring they are arranged for easy recognition by the tracking system. Smaller markers can be placed directly on the top surface without obstructing the projection, while larger markers may require a dedicated structure for support.



Figure 5-7 building prototype with hemispherical reflective markers

5.4.2 System Calibration

Before starting the calibration, ensure the prototype is prepared according to the guidelines in section 5.4.1 and placed within the tracking system's range so that all markers are visible. The physical prototype should also be aligned with the chessboard to match the 3D model's reference system orientation. Next, create a new rigid body within the Motive software by

selecting all the points associated with a specific marker constellation. Each rigid body should have a unique identifier, especially if multiple prototypes are used in a single session. Finally, an external tool is used to export the artifact calibration parameters. This tool reads data from Motive and automatically calculates the rotational matrix, which defines the artifact's orientation relative to the projectors.

5.4.3 Execution of Projection Mapping

Create a 3D building model with UV map and export it as obj. file. Then the 3D obj file and textures images (shown in Figure 5-8 and 5-9) are uploaded to SPARK platform, As shown in Figure 5-10. The 'Add Images' tab displayed on the left side of Figure 5-10, allows users to select from a list of "Images" assets associated with the session. To apply an image to the 3D model's mesh, the user drags and drops it onto the desired location while holding down the left mouse button. This tab also provides the option to link or upload new assets to the session. The 'Edit Asset' tab displayed on the left side of Figure 5-10 provides the mapping function on the overall categories of the building appearance, such as wall and roof.

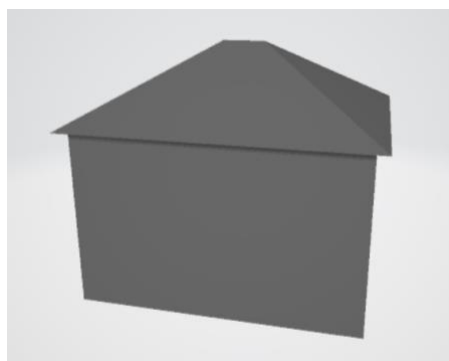


Figure 5-8 Building 3D obj. file



Figure 5-9 Texture images



Figure 5-10 Architectural design interface

Figure 5-11 shows the daylight simulation located in Milan, from the time of sunrise to sunset. The parameters firstly to input were latitude as 40, longitude as 12, time zone as 2, and date as 21/08/2022. By adjusting the time toolbar, we had a continuous daylight simulation of the day.

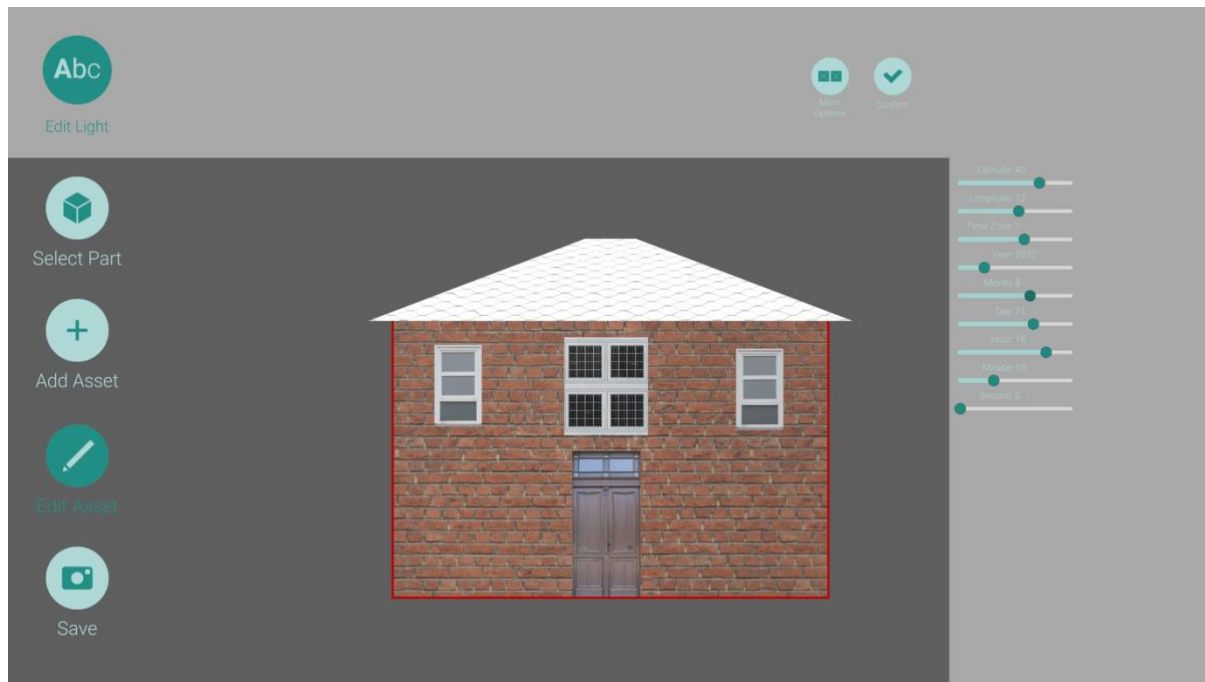


Figure 5-11 Daylight simulation interface with building model

Figure 5-12(a,b) shows the simulation at 15:00 and 16:00. By rotating the building prototype on 16:00, real time tracked mapping was applied, as shown in Figure 5-12(c,d). The simulations of both building components and daylight are quite natural, especially the shadow effects under the simulated daylight, which shows the very a realistic mapping with the building. As can be seen from the Figures 5-12(a,b), the changes of the shadows are clearly and subtly depicted. By comparing figures 5-12(b,c,d), the different shadow effects of the various building orientation on the same specific time could be discovered. The simulation of orientation 1 shows direct sunlight on around half of the wall and through around 1/4 of windows. And sunlight nearly doesn't shine on the front wall of building under orientation 2, while orientation 3 shows the opposite result. These simulation results can be applied to architectural design decisions regarding building orientation in relation to environmental factors. This includes considerations such as the overall sun illumination rate, as well as optimizing sunlight exposure based on whether the building is located in hot or cold regions. Such insights can help designers

increase or reduce sunlight exposure at specific times, enhancing energy efficiency and thermal comfort.



(a) simulation of orientation 1 at 15:00



(b) simulation of orientation 1 at 16:00



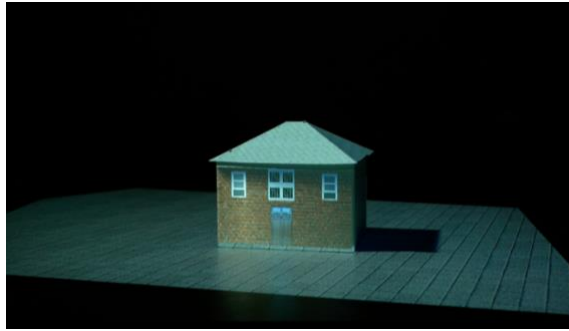
(c) simulation of orientation 2 at 16:00



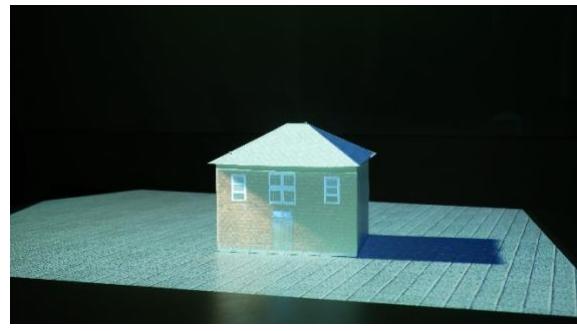
(d) simulation of orientation 3 at 16:00

Figure 5-12 Daylight simulation with building design 1

We did the same simulation at 15:00 and 16:00 of the day with another building design, as captured in Figure 5-13. And adjusted the window design according to light beam, as shown in Figure 5-14.



(a) simulation of orientation 1 at 15:00



(b) simulation of orientation 1 at 16:00



(c) simulation of orientation 2



(d) simulation of orientation 3

Figure 5-13 Daylight simulation with building design 2



(a) simulation of orientation 1



(b) simulation of orientation 1 with different window design

Figure 5-14 Simulation of building design 2 with real-time adjustable window design

The color brightness of roof and wall were changed to the opposite side from the previous design. A comparison between Figure 5-12 and Figure 5-13 reveals that the simulation effectively demonstrates the significant difference of sunlight effects on the different color

brightness of building components. Moreover, since white color reflect more sunbeam than darker colors, the shadows of on the wall appears deeper on the red wall, providing a realistic representation of shadow behavior. This variation in color and shadow not only enhances visual realism but also influences the perceived temperature of building components, offering valuable insights into thermal comfort from a human perception perspective.

Furthermore, the style and position of the windows were modified as shown in Figure 14(a,b), to change the direct sunlight penetration into indoor spaces. The window modification was implemented in real-time during the simulation, enabling dynamic adjustments and immediate feedback. This real-time capability significantly enhances architectural design collaboration by providing instant information on design changes and their impacts, thereby supporting more informed and efficient decision-making processes.

5.5 User Survey for Evaluating SAR-based Daylight Simulation

5.5.1 Survey Design

We applied sense of presence evaluation to validate the visualization quality and individual's subjective experience of presence within a mediated environment of the proposed system. The evaluation was conducted by a survey in which the overall structure was referenced from the ITC-sense of presence inventory (Lessiter, J. et al., 2001). Presence, in the context of media and technology, refers to the psychological state in which the user perceives themselves as existing within a virtual or simulated environment rather than merely perceiving the environment as an external object (Thornson et al., 2009). This inventory was developed by the International Society for Presence Research to provide a cross-media tool for assessing the user's sense of presence, which is considered a key factor in the success and effectiveness of various digital experiences, from virtual reality to video games (Lessiter et al., 2001). The

factors of sense of presence could be divided into naturalness, spatial presence and engagement, and each of the factors is evaluated individually (Lessiter et al., 2000). To make the questionnaire more comprehensive and reasonable, we revised the questions from the existing survey that commendably describe the three factors and are suitable for our proposed system. We also define each factor by multiple categories. The designed survey inventory is presented in Table 5-1, 5-2 and 5-3. Likert scale was adopted for the questionnaire to rate each item from 1 to 5.

Table 5-1 Naturalness factor inventory.

Categories	Questions
Realness	Watching the display objects was just as natural as watching the real world.
	I could imagine having to touch or grasp the display objects.
	How real seemed the contents in comparison with the real world?
	How real seemed the contents in comparison with an imagined world?
Content Quality	How were the quality of color and texture?
	To what extent was what you watched of the displayed contents congruent to other experiences in the real world?
	The displayed environment seemed natural.
Display Environment	I felt that the displayed environment was part of the real world.
Sense of objects	The scenes depicted could really occur in the real world.
	I had a strong sense that the objects were solid.
	The content seemed believable to me.

Table 5-2 Spatial presence factor inventory

Categories	Questions
Impression in the real space	I was able to imagine the arrangement of the spaces presented in the displayed environment very well.
	Did the virtual objects appear to be (visualized) on a screen, or did you have the impression that they were located in space?
	Did you have the impression of seeing the virtual objects as merely flat images or as three-dimensional objects?
	How much did you have a sense you could “being there” when watching virtual environment?
Sense of interaction	I could imagine interacting with the sunlight and to cause shadow effects.
	I could imagine reaching out and touch the display objects.
Sense of temperature	I could imagine to sense that the temperature changed to match the scenes in the displayed environment

Table 5-3 Engagement factor inventory

Category	Questions
User’s attention	I devoted my whole attention to the application.
	The topic of the activity made me want to find out more about it.
	To what extent did events such as noise occurring around you distract your attention from watching the contents?
	I paid more attention to the displayed environment than I did to my own thoughts
	The content appealed to me.
Experience satisfaction	How much did you enjoy yourself during the experience?
	Would you like to repeat the experience you just had?
	I would have liked the experience to continue.
Memories of Experience	I vividly remember some parts of the experience.
	I lost track of time.
Experience recommendation	I’d recommend the experience to my friends.

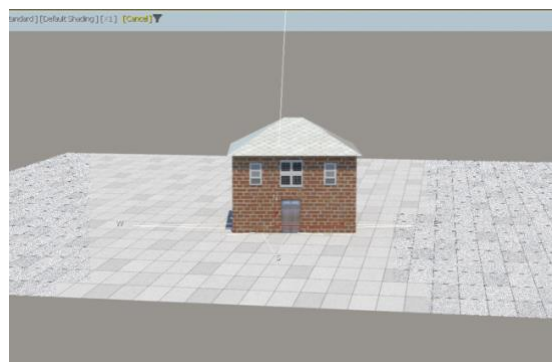
5.5.2 Results and Discussion

We recorded simulations of the proposed SAR system and 3dx Max in the same building designs and timeline sets, as demonstrated in Figure 5-15. Following the simulations, participants were asked to complete a questionnaire based on a designed survey inventory after viewing the two videos. The survey was created by Qualtrics, an online survey tool, and allocated to 50 professionals who are working or have experience in the architectural field.

Tables 5-4 summarize the results of the sense of presence survey according to the categories of naturalness, spatial presence, and engagement factors. Overall, there is a big difference in the level of naturalness and spatial presence between SAR-based simulation and software-based simulation. The difference in engagement level is relatively small. From the perspective of naturalness, the sense of objects of SAR (3.98) is very good and the realness of SAR (3.74) also shows a high score. Software content quality has the highest score among naturalness factors, but it is still lower than SAR. From the point of view of spatial presence, SAR demonstrates considerable advantage in the spatial impression (4.13) and sense of interaction (4.34). The overall score of SAR (3.92) and software (1.61) shows that they share the highest level of difference in spatial presence. In terms of engagement, both SAR and software show a satisfied user engagement level, and SAR is slightly better than software.



(a) SAR-based simulation



(b) software-based simulation

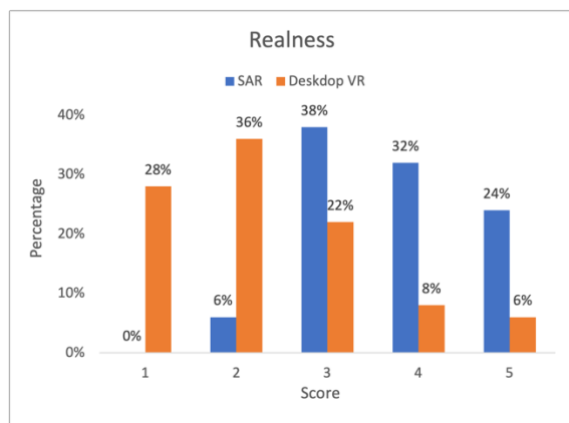
Figure 5-15 Video captures of SAR-based simulation and software-based simulation

Table 5-4 Descriptive statistics of sense of presence survey

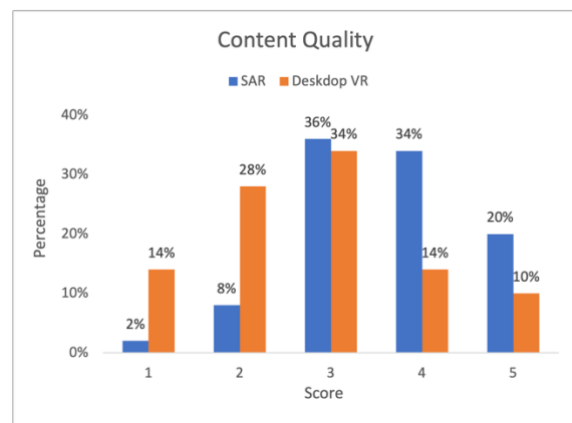
Factors	Categories	SAR	Desktop
Naturalness	Realness	3.74 (0.890)	2.28 (1.132)
	Content quality	3.62 (0.957)	2.78 (1.154)
	Display environment	3.54 (1.004)	2.02 (0.927)
	Sense of objects	3.98 (0.836)	1.92 (0.935)
Spatial presence	Impression in the space	4.13 (0.877)	1.90 (0.831)
	Sense of interaction	4.34 (0.789)	1.76 (0.736)
	Sense of temperature	2.29 (1.139)	1.78 (0.782)
Engagement	User's attention	3.36 (1.036)	3.00 (1.200)
	Experience satisfaction	3.43 (0.906)	3.18 (1.090)
	Memories of Experience	3.57 (0.980)	3.06 (1.066)
	Experience recommendation	3.93 (0.809)	3.64 (0.768)

Note: Numbers represent the mean (standard deviation) of the corresponding elements.

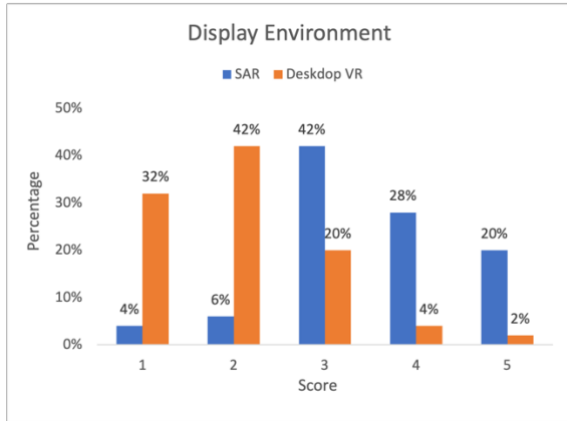
Moreover, the respective scoring ratios of SAR-based simulation and desktop-based simulation on each evaluation factor are diagramed in Figures 5-16, 5-17 and 5-18. It can be seen that SAR-based simulation has higher top-tier scores (3-5) in naturalness and spatial presence factor. These two simulation methods share a relatively similar distribution of scores in engagement factor.



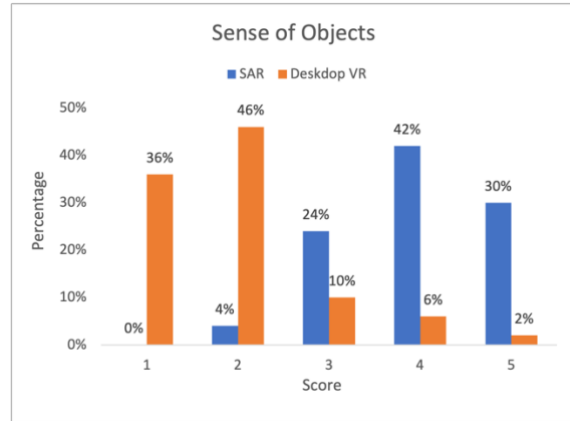
(a)



(b)

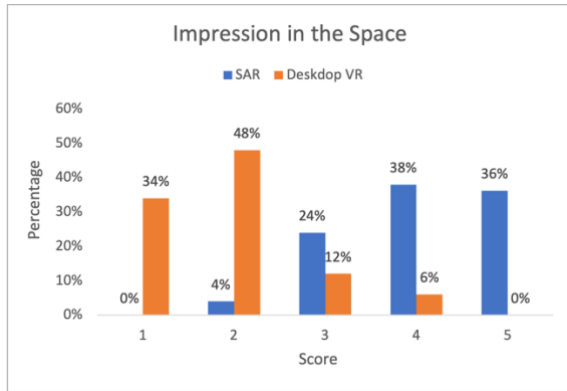


(c)

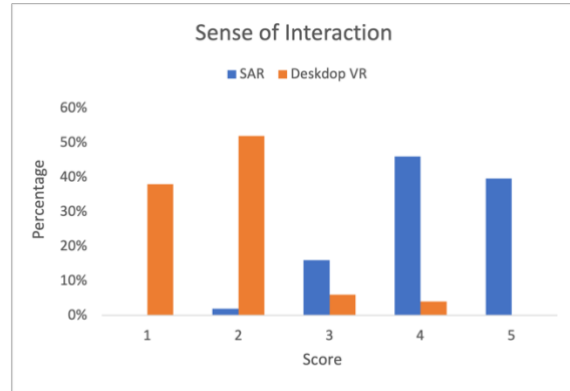


(d)

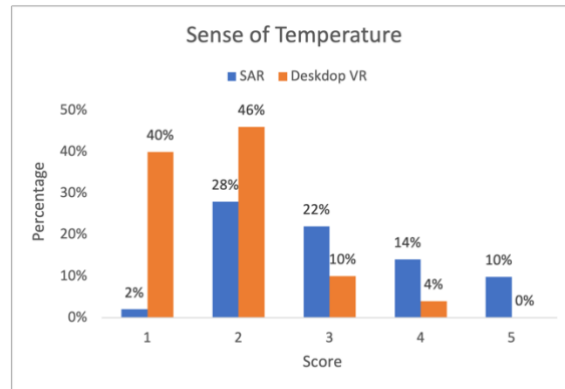
Figure 5-16 Scoring ratio histogram of naturalness factor.



(a)

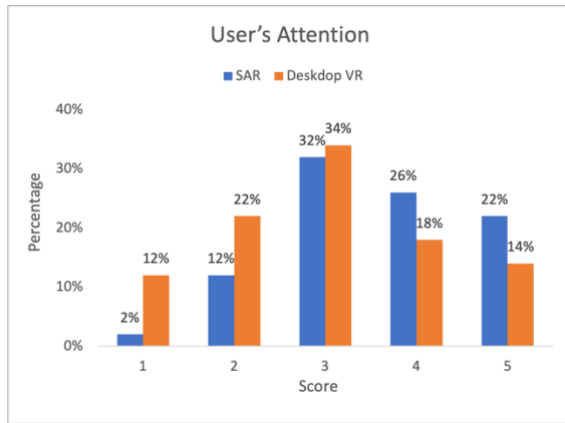


(b)



(c)

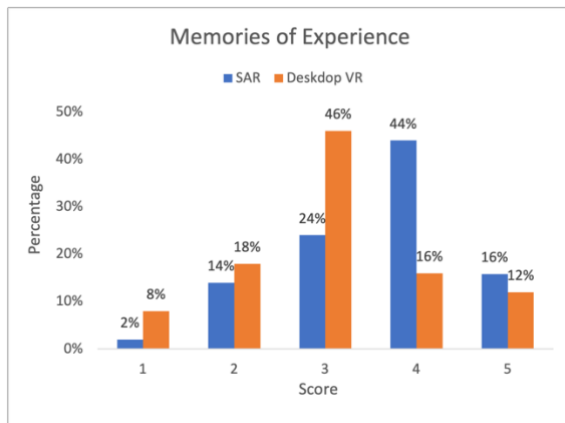
Figure 5-17 Scoring ratio histogram of spatial presence factor.



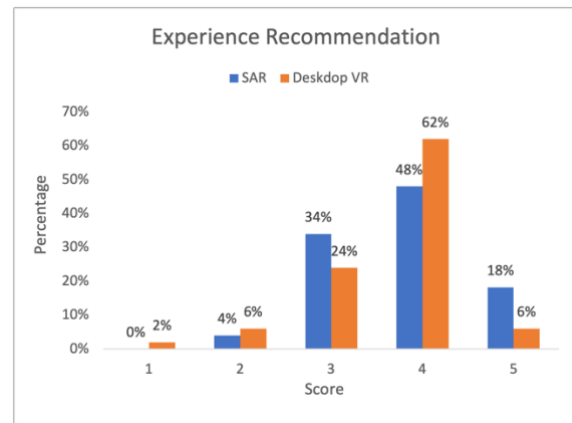
(a)



(b)



(c)



(d)

Figure 5-18 Scoring ratio histogram of engagement factor.

Furthermore, a paired t test was applied to evaluate whether there is a significant difference between the means of the scores of SAR-based simulation and desktop-based simulation (Kim, 2015). Assume the confidence level as 95%, according to the t distribution table, P (2-tailed) in this case is around 2.0105. The results are tabulated in Table 5-5. Since the t values of the 11 categories are larger than P, it could be said that there are significant differences between SAR-based simulation and desktop-based simulation in terms of all the categories. Therein, impression in the space and sense of interaction aspects show extreme differences, while content quality, user's attention, sense of temperature and experience satisfaction aspects indicate small differences.

Table 5-5 Results of paired t test of SAR-based simulation and desktop-based simulation

Different categories	Paired differences			t	df	P (2-tailed)
	mean	standard deviation	standard error			
Realness	1.46	0.242	0.034	30.177	49	2.0105
Content quality	0.84	0.197	0.028	15.069	49	2.0105
Display environment	1.52	0.077	0.011	69.752	49	2.0105
Sense of objects	2.06	0.098	0.014	74.133	49	2.0105
Impression in the space	2.23	0.046	0.006	171.791	49	2.0105
Sense of interaction	2.58	0.052	0.007	173.756	49	2.0105
Sense of temperature	0.51	0.357	0.050	5.055	49	2.0105
User's attention	0.36	0.164	0.023	7.755	49	2.0105
Experience satisfaction	0.25	0.184	0.026	4.803	49	2.0105
Memories of experience	0.51	0.086	0.012	20.864	49	2.0105
Experience recommendation	0.29	0.040	0.006	25.508	49	2.0105

Naturalness is closely linked to the concept of tacit knowledge, which refers to the experiential and intuitive understanding of daylight simulation and architectural design. One of the key reasons why SAR has good naturalness is its ability to enhance the user's perception of the real-world environment. By overlaying digital content onto the physical world, users are able to view the model design and daylight simulation in a more intuitive way, as they appear to be a part of their immediate surroundings. This integration of digital and physical elements can lead to a more immersive observation process, as the user's attention is not divided between the two. Also, the effectiveness of the SAR system in conveying a sense of reality might significantly benefit realness and content quality. Virtualization of the design process can sometimes alienate the body from the mind, leading to a more detached and rationalistic approach to design. In contrast, this system can help to bridge this gap by providing a more natural and embodied interface for designers to engage with their work.

With regard to spatial presence, one factor contributing to the excellent spatial presence of SAR could be its ability to integrate digital content seamlessly into the user's real-world environment. As users interact with virtual objects and information, they perceive these elements as an integral part of their physical surroundings, blurring the lines between the digital and the physical. This level of integration and coherence between the virtual and the real world is crucial in fostering a strong sense of spatial presence, as users feel that the digital elements are a natural extension of their immediate environment. Additionally, the personalized and context-sensitive nature of Spatial Augmented Reality experiences has been shown to reinforce the user's sense of spatial presence. By tailoring the digital content and interactions to the user's specific needs and preferences, the technology can create a more meaningful and immersive experience, fostering a stronger sense of "being there" within the augmented environment. Therefore, the proposed system is able to allow architects to explore and experience their designs in a more immersive and natural way, providing a better understanding of the spatial qualities and relationships of the proposed structure. This can lead to more informed design decisions and a more engaging design process for both the architect and the client.

In terms of engagement, one reason driving user engagement in Spatial Augmented Reality might be the "playground effect". The interactive and immersive nature of Spatial Augmented Reality enables users to engage in creative and playful experiences, leading to greater anticipated satisfaction with their purchase decisions. By blending virtual and physical environments, Spatial Augmented Reality provides users with a sense of realism and interactivity that traditional digital interfaces often lack, thereby fostering a more engaging and satisfying experience. On the other hand, SAR has the potential to enhance the visualization process by promoting critical thinking, meaning-making, and metacognition. The ability of SAR to merge virtual and real-time applications, allowing users to be immersed in realistic

experiences, has been a key driver of its educational applications. This interactive and engaging approach to learning can lead to more active and meaningful experiences. Satisfying Engagement could benefit collaboration and communication between various stakeholders involved in the design process. By improving multiple individuals to simultaneously interact with and visualize the same digital model, the proposed system can foster a more collaborative and iterative design process, leading to improved design outcomes.

5.6 Conclusion

Architectural design is a complex and multifaceted process that requires a deep understanding of the spatial and visual qualities of a proposed structure. In recent years, the integration of digital technologies has emerged as a transformative approach to enhancing the design process. However, these simulations often suffer from limitations such as time-consuming workflows and a lack of spatial awareness, which restrict their practical applications. To address these challenges, we developed a SAR-based daylight simulation system, which offers a more interactive and responsive approach to architectural design. This system uses solar calculation algorithm to generate the simulated daylight, and the interaction interface was developed from SPARK platform as a plugin tool by using C# computer language. The simulation results demonstrate good quality of both building textures, daylight beam and shadows. To evaluate the advantages of proposed system over software-based daylight simulation, we conducted a comparative study focusing on the sense of presence, measured across three dimensions: naturalness, spatial presence and engagement. The results show superiority of SAR-based simulation especially in naturalness and spatial presence. And the user engagement level of SAR is higher. Also, it could be suggested that this system has the ability to quickly transform architectural models into highly immersive virtual scenes, accessible and explorable by both professionals and the general public in the real space. Moreover, the system enables architects

to quickly evaluate and refine their designs based on the real-time feedback provided by the simulated daylight conditions, fostering a more iterative and responsive design process.

Future research could explore more on improving the system's interactivity to achieve seamless interaction between users and simulation models, which enabling users to interact with virtual content in a more natural and intuitive manner. For example, users could modify the daylight condition and building design by pointing on the building model, rather than a computer interface that we proposed in this research. To achieve this, more sophisticated tracking methods should be adopted.

Chapter 6 Conclusions and Future Research

6.1 Review of Research Background

Up until now, BIM-based AR design collaboration has been a popular means of presenting design solutions. However, AR technology does have some limitations, such as technical issues, negative user experiences, and the quality of visualized information. The use of spatial augmented reality (SAR) is gaining attention in architectural design, addressing the limitations of existing MR technologies. Unlike traditional MR-based visualization that overlays digital content onto the user's view of the physical world or the virtual world, SAR projects digital content directly onto physical surfaces, creating a seamless blending of the real and virtual environments. SAR has a high level of photorealism that could necessarily deceive the human eye and seamlessly integrate virtual objects into physical environments. It has been found that SAR-based design collaboration has comparative advantages in terms of immersion, spatial perception, and visualization capabilities compared with IVR or AR visualization.

6.2 Research Objectives and Major Findings

Firstly, we first propose a conceptual framework for BIM-based projection mapping using spatial augmented reality technologies for better architectural design collaboration through rapid prototyping of BIM-based 3D models. Through the BIM-based SAR framework, the study presents the implementation procedures and technical requirements necessary to generate 3D models and display surface textures on physical building models. We also implemented and tested the feasibility of the proposed framework using a projection mapping tool to project virtual building models on cube-shaped objects. The result was a stable display of building models through projection mapping, thereby demonstrating the potential to solve the current limitations of AR-based design collaboration activities. The results of the control elements

setting show a better definition of bigger model size, projection distortion issues on curved and angled surfaces, and a clearer stereo projection view in darker environments.

To further advance the study, we address automatic geometric calibration by applying a projector-camera system. Geometric calibration is the most essential technical component of SAR to project designed texture images on a certain location of a targeted object in the 3D world, and there are many geometric calibration systems developed to settle it. For the simpler, more compatible application and operation of SAR on building design visualization, we developed a user-friendly automotive calibration system. This system adopted a variety of machine vision algorithms, using an uncalibrated projector-camera pair to detect and calculate the corresponding position of markers relative to the projector image frame to establish the correspondence between the projector and physical models. We validated the geometric calibration accuracy through both single and multiple-volume types of building models and the different location settings of the projector-camera pair, and the results suggest an overall small error.

Lastly, we explored daylight simulation for architectural design by applying SAR technology. Despite the benefits of using existing MR technologies for daylight simulation and visualization, their applications for visualizing architectural design have been criticized due to a lack of realism and difficulty in creating a collaborative environment for design review. The perceived spatial location of virtual objects within these simulations may be ambiguous, leading to potential confusion and disorientation for users. Another limitation is the difficulty in effectively representing and communicating the complex lighting patterns and color variations that can occur in real-world daylit spaces. Considering that building design images can be projected through a beam of light onto a physical model, it is expected that daylight

simulation and visualization using SAR would create a more real-like environment, Simulating various lighting conditions for design review. Therefore, we developed a SAR-based daylight simulation system, which offers a more interactive and responsive approach to architectural design. This system uses a solar calculation algorithm to generate the simulated daylight, and the interaction interface was developed from the SPARK platform as a plugin tool by using C# computer language. The simulation results show good quality of both building textures, daylight beams and shadows. To demonstrate the advantages of the proposed system over software-based daylight simulation, we conducted a sense of presence comparison comparing SAR and software in terms of naturalness, spatial presence, and engagement. The results show the superiority of SAR-based simulation, especially in naturalness and spatial presence. And the user engagement level of SAR is higher.

6.3 Contributions of the Study

Firstly, a framework of spatial augmented reality rapid prototyping with a BIM model was tested. Traditional AR uses sensors in head-mounted displays or handheld devices for 3D registration, which can cause inaccuracies. The proposed BIM-integrated SAR approach uses reference points to register the virtual and physical models. This allows for stable and precise projection without wearable devices or continuous sensor input. This framework offers a more interactive and intuitive design review process using SAR. Different design options (materials, component positions) can be projected onto a physical model, facilitating collaboration.

In terms of the marker-based automatic calibration system for SAR, the advantages of our system are that it does not require projector-camera calibration, and the whole object-projector calibration process is integrated into one phase. The only manual operation of our system is to place a white panel coincident with a model surface and capture an image of the projection

area, which is easy to understand and operate for users in the ACE industry. Also, our system allows simple input of the designed texture images of BIM models to be more compatible with BIM appearance designs.

Furthermore, it could be suggested that the developed SAR daylight simulation system has the ability to quickly transform architectural models into highly immersive virtual scenes that can be easily explored by both professionals and the general public in real space. And it allows architects to quickly evaluate and refine their designs based on the real-time feedback provided by the simulated daylight conditions, enabling a more iterative and responsive design process.

6.4 Limitations and Future Research

The proposed marker-based automatic calibration system has only been tested on the building models constituted by planar surfaces. Curve surfaces are expected to be tested for more comprehensive applications on various types of buildings. Since curve surfaces may result in more complex perspective projection when projecting images into 3D space, and the perspective distortion would be inconsistent on the same curve surface, further calculation methods need to be explored to estimate the distortion parameters. Moreover, we only applied one PROCAM pair to demonstrate the feasibility of our system. If another PROCAM pair is installed to project the other sides of the model, there will be overlapping projection areas where one more layer of projection light is unbelonging to the texture image.

Another future research could focus on improving the system interactivity to achieve seamless interaction between users and a BIM environment, which enables users to interact with virtual content in a manner that feels natural and intuitive. For example, changing the daylight condition and building design by finger-pointing at the building model rather than using a

computer interface is what we proposed in this research. To that end, more sophisticated tracking methods should be adopted.

6.5 Conclusions

All in all, by applying SAR in architectural design visualization and collaboration, design alternatives can be quickly projected on a physical mass model of a building, supporting collaborative design between project participants. For example, textured models of varying design alternatives can be generated and visualized individually using a projector during collaboration, allowing more interactive design comparison. If needed, users are able to make changes to the building design, which can be and quickly inserted into the SAR system. Thus, the updated design alternatives can be shown promptly on the physical model. For this process, only the presenter needs to operate the equipment, and the users do not have to hold or wear any devices during design collaboration activities. As a result, non-technical users can easily and intuitively review building models without feeling the discomfort or dizziness of wearing an AR device. Users can even move around to view models from different angles, similar to how a real building would be observed. According to the presented mapping results, high-quality details from various perspectives were easily observed, such as areas with a lot of visual content and the building model edges. Through SAR technology, building project participants could also share a common reference point in the projected SAR environment. This could potentially be beneficial for effective model-based collaboration between participants since it would enable them to communicate face-to-face with a shared view of building models.

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