Dissertation

The Development of Design Support System for Participatory Design of Community Environment Improvement Using Mixed Reality

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Abstract

This research aims to use Mixed Reality (MR) technology to develop a new design support system to support the participatory design of community environment improvement. Furthermore, this design support system contributes to aiding the professionals to make intuitive design perception, accurate design deduction, and convenient design adjustments on-site in the design concept stage. In addition, it contributes to narrowing the semantic differences between professionals and citizens in the design deliberation stage.

Firstly, to address the lack of an effective tool for participatory design, we designed and developed an MR design support system called HoloDesigner on Microsoft Hololens. Unity 3D game engine was employed as the core development platform. Through the four crucial steps, creating interactive interfaces, developing design functions, loading design data, establishing interactivity and visualizations, HoloDesigner was implemented successfully. We then demonstrated its main workflow and functionalities. The results proved that HoloDesigner could successfully achieve on-site 3D visualization and real-time manipulation to control 3D models in the real community environment, which provided the potentials to support participatory design in community environment improvement.

Then we applied HoloDesigner to the community environment improvement to assisting professionals in making design proposals on-site. Specifically, we performed an on-site design experiment with sixteen participants in a typical community environment improvement scene using HoloDesigner. The results showed that HoloDesigner could provide users with intuitive design perception, accurate design deduction, and convenient design adjustments, thus effectively assisting them in making design proposals on-site in the design concept stage.

Subsequently, we applied HoloDesigner to narrowing the semantic differences between professionals and citizens in the design deliberation process. Concretely, we recruited twelve lay people to involve in a design experiment for a typical campus

community public space with HoloDesigner. The results suggested the most participants could understand accurately the design proposal proposed by the professional design team through the 3D visualization of HoloDesigner. Meanwhile, the results also validated that the most participants could convey their design demands clearly by adjusting the design proposal in real-time using HoloDesigner.

In conclusion, this research presented an MR design support system HoloDesigner successfully and validated its effectiveness for supporting participatory design in different design stages of community environment improvement through two empirical design experiments.

Keywords: HoloDesigner; Professionals; Citizens; On-site design; Semantic differences

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The last, the special acknowledgement must go to my parents and my wife for their endless love and support.

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DAN YUZE

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Chapter 1. Introduction

1.1 Research contribution

Our contribution in this paper is developing a Mixed Reality (MR) design support system called HoloDesigner to facilitate the participatory design in community environment improvement. We developed this design support system on the Microsoft HoloLens hardware platform to render on-site 3D visualization and offer real-time interactions for 3D design objects in the physical environment. Through two community design experiments, we examined how HoloDesigner assisted professionals in making intuitive design perceptions, accurate design deduction, and convenient design adjustments on-site in the design concept stage, and how HoloDesigner helped citizens to understand the professional design proposal and express their design demands in the design deliberation stage.

1.2 Research background
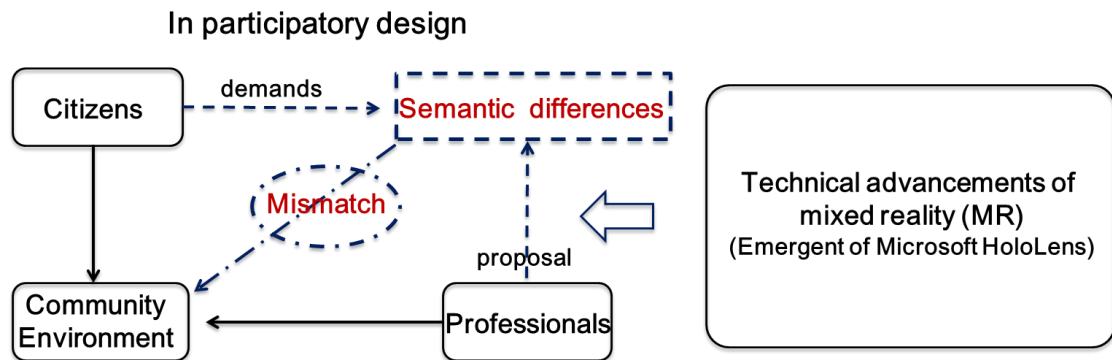
Fig. 1.1. The logic diagram of research background.

The rapid urbanization process profoundly influences citizens' everyday lives in recent years (Sennett, 2003). Thus, citizens put forward more demands for the community environment carrying on their daily lives (Huang et al., 2014). Nevertheless, the community environment where citizens live is always decided by professionals through making design proposals (Friedman, 1987). As the semantic differences

between citizens and professionals, there are always some mismatches between the demands of citizens and the design proposal from professionals (Stamps III et al., 2005).

As a result, citizens have been gradually encouraged and invited to involve in the community environment design process led by professionals, from demands collection to design communication. However, with the lack of practical tools, there are still some difficulties for professionals making design proposals effectively on-site and for citizens understanding the professional design proposal accurately, thus hardly narrowing the misunderstandings caused by the semantic differences between citizens and professionals.

Technological advancement provides more possibilities to improve the participatory design process in community environment improvement (Al-Kodmany, 2001). Significantly, the recent Mixed Reality (MR) technology can create a new visual environment where real and virtual objects co-exist and interact in real-time (Milgram & Kishino, 1994). MR technology offers the potentials to support professionals to make intuitive design perception, accurate design deduction, and convenient design adjustments on-site. Meanwhile, MR technology displays the possibilities for citizens to understand the professional design proposal and express their demands clearly.

The logic of this part is shown in Fig.1.1.

1.3 Literature review

1.3.1 Participatory design theories and practices in community environment improvement

Specifically, the earliest participatory design work in urban planning and design can date back to the 1950s. The developed countries were in economic recovery and rapid urbanization after World War II (Glass, 1977). The extensive urban development mode triggered increasing social problems. Affected by the revival of liberalism and the civil rights movement, the public's self-awareness and civil rights began to awake.

The citizen began to organize and request spontaneously to participate in the decision-making process of urban planning (Cunningham, 1972). At the same time, the urban planning field began to reflect the urban maladies caused by modern architectural movement and the social problems led by the imbalanced political, economic, and social mechanisms (Sennett, 2003). The planning field generally believed that this design method focused on the physical space form ignored the citizen's needs and lacked consultation opinions from the public (Friedman, 1987). In 1962, Davidoff and Reiner published "A Choice. Theory of Planning", which established the theoretical basis of public participation in urban planning with pluralism. Based on the community's overall development concept, the US government empowered the cities to assist low-income communities (Friedman, 1987). In 1969, Britain took the lead in institutionalizing public participation in policies and then started the community-building movement (Hatch, 1982). In the same year, the American sociologist Arnstein (1969) proposed the citizen participation ladder theory, which divided participation into steps according to the degree to examine the role of citizens at different levels. Also, Japanese Machizukuri started in the 1960s. It had developed gradually from the special protection for historic districts to the comprehensive community building, mainly involving citizens using their power to improve living and working environment (Kusakabe, 2013).

In 1973, the United Nations World Environment Conference issued the declaration "Environment Created by People," which provided a theoretical guarantee for participatory design in urban planning (Branch, 1985). In 1976, the United Nations held the Habitat International Council, focusing on the importance of community environment improvement (Branch, 1985). In 1977, Alexander published the "A pattern language, towns · buildings · construction." He believed that the stakeholders were more aware of their demands than designers and encouraged them to participate in the

design process (Alexander et al., 1977). Since then, the participatory design process in community planning practice was further promoted, and the United States has developed a network of design centers that includes 70 community assistance groups.

Since the 1980s, the participatory design gradually gained a foothold in the urban planning field, accumulated a lot of practice experience, and established a theoretical framework. Wates and Knevitt (2013) summarized participatory design methods in urban planning fields in the UK in the 1990s. The methods mainly included social surveys, public gatherings, design meetings, visits to other projects, PPT explanations, model creation, display, etc., which promoted innovative methods by professionals to understand and communicate with the public in a more creative way.

Since the 2000s, participatory design in urban planning has further developed and deepened. To overcome the professional symbolic barriers of the public and strengthen the effectiveness of participation, Henry Sanoff (2011) invented a method of expressing people's various activities in various environments with graphic symbols. This method was convenient for users to choose the suitable patterns for expressing design demands based on the specific behaviors and participated in the design process of the participatory workshops.

1.3.2 MR participatory design support system development
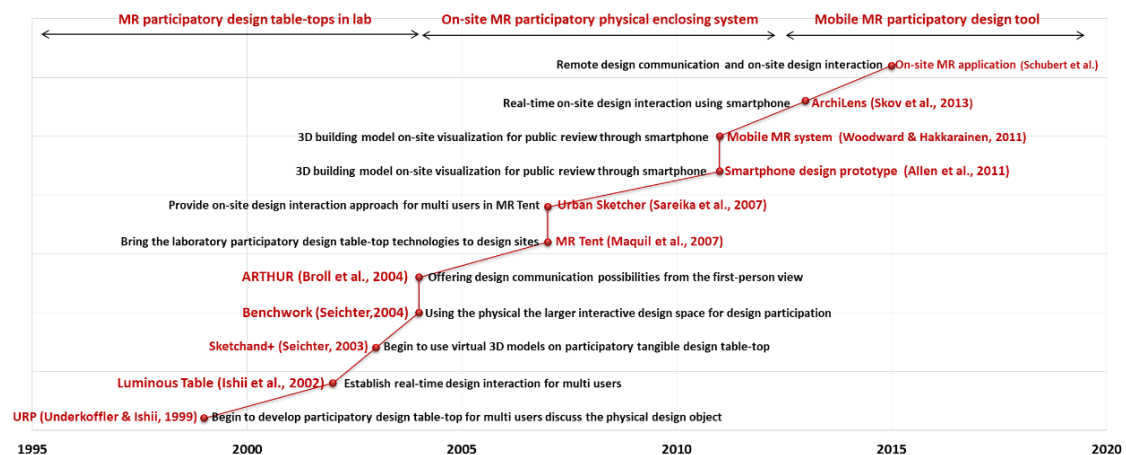
Fig. 1.2. The development progress of MR participatory design support system.

In recent years, the new computer graphics technology MR was used to develop the support system for participatory design, which experienced a long process including three primary stages (Fig. 1.2).

1.3.2.1 MR participatory design table-top

The earliest work can date from the 1990s. The design table-top began to be implemented as the main tool to support participatory design. The design table-top universally integrated some complicated hardware such as camera, projection, physical table-top, and external display (Oksman et al., 2014). Typically, URP and Luminous Table realized real-time environmental analysis and design sketches inputting on the table-top surface in the MR environment (Underkoffler & Ishii, 1999; Ishii et al., 2002). Nevertheless, they used physical models that must be prepared in advance and unable to adjust according to the specific requirements. So the following work began to use digital models. For example, Sketchand+ used a digitizer tablet as the inputting interface to create 3D digital models viewed by the head-mounted display (HMD) (Seichter, 2003). Then the interaction mode was upgraded further. Benchwork used a giant digital board as the inputting interface and participatory design space (Seichter, 2004). ARTHUR, the more advanced MR participatory table-top, firstly provided users with gesture control to edit 3D design models from the first-person view (Broll et al., 2004; Schieck et al., 2005; Wang, 2013). Nevertheless, these MR participatory design table-tops always were blamed for never bring virtual design models into the actual environment for design interaction (Schubert et al., 2015).

1.3.2.2 On-site MR participatory design physical enclosing system

An on-site physical enclosing system MR Tent came up to echo the real environment, which brought the technologies usually available only in laboratory settings to the actual community scene (Maquil et al., 2009). Subsequent MR application, Urban Sketcher created an on-site sketch inputting approach for MR Tent

(Sareika & Schmalstieg, 2007). However, MR Tent involved several complex devices and on-site installations (Sareika, 2010). Using the fixed webcam, MR Tent could only support some limited viewpoints for users to experience the MR scene (Schubert et al., 2015).

1.3.2.3 Mobile MR participatory design support system

Thus MR participatory design support system development began to turn to mobile devices. Significantly, the smartphone assembled diverse functions and became more portable recently (Oksman et al., 2014; Gill & Lange, 2015). The early MR participatory design systems on the smartphone mainly focused on assisting citizens in visualizing the potential 3D design objects at the design site (Allen et al., 2011).The lack of design functions, the early design systems could not support users to express their design demands clearly (Schubert et al., 2015). Thus Skov et al. (2013) proposed ArchiLens on the smartphone. This system could support users make real-time control for the design parameters (position, shape, and size) of virtual design objects on-site.

Nevertheless, the 2D screen display based on the smartphone could scarcely realize immersive design perception (Wang, Chen, & Chen, 2018), and the rough tangible interaction could hardly support accurate design manipulation (Chi et al., 2013). As stuck at the limited hardware performance, few MR participatory design systems on mobile devices effectively supported participatory design.

1.3.3 Summary

We summarized the participatory design frame through the literature review using the MR design support system in community environment improvement.

1.3.3.1 Participants

In the urban development process, professionals were the technicians, organizers, or coordinators to facilitate communication and make the design process open and democratic. As the actual users of community space, citizens had the power to express

their demands about the design and construction of their community environment.

1.3.3.2 Participatory design methods

Regarding the participatory design method, first, the symposium was held to collect relevant design demands from citizens. Second, when the planning and design project faced critical issues, it was usual to retain an expert representative meeting to seek the corresponding solutions. Third, the public participated in on-site design interaction and made preliminary proposals instead of expressing their design demands through questionnaires or forums. Direct public participation was highly targeted, and the effect of the involvement would be significantly improved compared to expert representative meetings and symposiums. Fourth, the internet-based network display and voting solicitation had expanded the impact of project display and enhanced interactivity.

In recent years, computer graphics technologies began to be used to develop the design support system for participatory design.

1.3.3.3 Participatory design stages and contents

The participatory design process of the community environment improvement could be divided into four stages: design investigation, design concept, design deliberation, and design construction.

The contents of the design investigation mainly included basic data collecting and sorting, community problem integration, on-site surveys, and symposium discussions. The contents of the design concept mainly included preliminary design, field interaction, and feasibility analysis. The contents of design deliberation mainly included design display, design evaluation or feedback, workshop, fixed-point exhibitions, and public explanation. The contents of design construction mainly included joint reconstruction, community resource reuse, environmental quality improvement, and community culture cultivation.

1.4 Innovations

1.4.1 The selection of hardware

From the literature review above, we could find that the conventional MR participatory design support system mainly depended on some complicated devices, limiting users' usage freedom in the design process. In recent years, the mobile smartphone or tablet was used as the primary hardware to improve the portability of the MR participatory design support system. At the same time, the 2D visualization and stiff manipulation affected the users' design experience.

Fig. 1.3. Microsoft HoloLens.

We selected Microsoft HoloLens (Fig. 1.3), the most advanced wearable MR glasses, as the core hardware in this research. Microsoft HoloLens has been used in some critical fields, like medicine, pedagogy, geography, etc. Its technical characteristics, such as 3D visual display, natural interaction modes, and spatial depth perception, match our research purposes.

1.4.2 The comparison between HoloDesigner and conventional MR participatory design support systems

Features / Systems	Visualization	Interaction	Installation	Mobility	Spatial depth
HoloDesigner	3D on-site holographic Visualization	Holographic interaction gaze & gesture	Simple	Good	Yes
URP (Underkoffler & Ishii, 1999)	2D off-site Visualization	No	Complicated	No	No
Luminous Table (Ishii et al., 2002)	2D off-site Visualization	Tangible interaction a digitizer tablet	Complicated	No	No
Sketchand+ (Seichter, 2003)	2D off-site Visualization	Tangible interaction a digitizer tablet	Complicated	No	No
Benchwork (Seichter, 2004)	2D off-site Visualization	Tangible interaction a larger digital board	Complicated	No	No
ARTHUR (Broll et al., 2004)	2D off-site Visualization	Tangible interaction A digital wand	Complicated	No	No
MR Tent (Maquil et al., 2009)	2D on-site Visualization	Tangible interaction a digitizer tablet	Complicated	No	No
Smartphone Design Prototype (Allen et al., 2011)	2D on-site Visualization	Tangible interaction smartphone touching screen	simple	Good	No
Mobile MR System (Schubert et al., 2015)	2D on-site Visualization	Tangible interaction smartphone touching screen	simple	Good	No
ArchiLens (Skov et al., 2013)	2D on-site Visualization	Tangible interaction smartphone touching screen	simple	Good	Weak

Fig. 1.4. The comparison between HoloDesigner and conventional MR participatory design support systems.

Compared to the conventional MR participatory design support systems, HoloDesigner could achieve 3D on-site visualization and real-time holographic interaction for the design objects and offer simple installation, good mobility, and accurate spatial depth perception (Fig.1.4).

1.4.3 The comparison between HoloDesigner and existing design applications on Microsoft HoloLens

Applications \ Features	HoloDesigner	HoloSketch (Microsoft, 2018)	Holograms (Microsoft, 2017)	3D Viewer (Microsoft, 2018)
Aiming at Participatory Design	Yes	No	No	No
Design functions	Rich (Six design functions)	Poor (Movement and adjustment)	Poor (Movement and adjustment)	Poor (Movement and adjustment)
Spatial depth perception	Yes	Yes	No	No
Regular maintaining	Usually	No (not available in Microsoft store)	No	A few
Stability	Normal	Poor	Poor	Normal
Design data	3D models and 2D texture maps (Storing in cloud)	3D models (storing in cloud)	No import approach	3D models (storing in cloud)

Fig. 1.5. The comparison between HoloDesigner and existing design applications on Microsoft HoloLens.

Compared to the current related design applications on Microsoft HoloLens, HoloDesigner was developed to aim at supporting participatory design. Thus, it was equipped with some essential design functions and flexible cloud storage space. As developed in-house, HoloDesigner can achieve regular maintains by us and guarantee its stability (Fig. 1.5).

1.5 The focus of this research
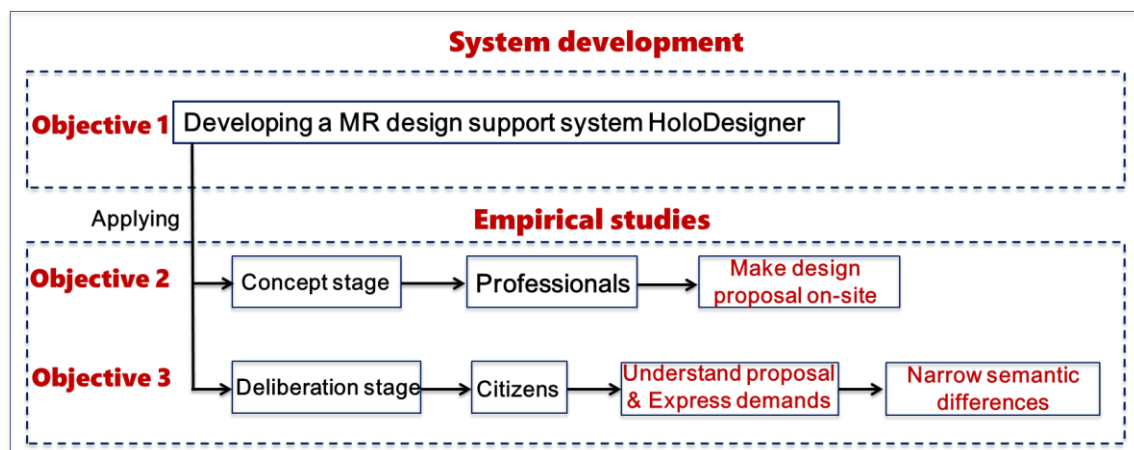
Fig. 1.6. The focus of this research.

In this research, we focused on three main research objectives (Fig. 1.6). First, we

intended to use MR technology to implement a design support system called HoloDesigner for supporting participatory design. Second, we planned to apply HoloDesigner in the design concept stage to help professionals' on-site design perception, deduction, and adjustment, thus facilitating them making design proposals on-site. Third, we planned to apply HoloDesigner in the design deliberation stage to support citizens' design understanding and demands expression, thus narrowing the semantic differences between the professionals and citizens.

1.6 The organization of dissertation

The main contents of the dissertation are organized into three parts (Fig. 1.7). After this introduction, Chapter 2 proposes a conceptual framework of the MR design support system named HoloDesigner and describes its development and main functionalities. Chapter 3 examines the effectiveness of HoloDesigner for supporting professionals in the design concept stage through a design experiment with sixteen participants. Chapter 4 validates the feasibility of HoloDesigner for supporting citizens in the design deliberation stage through a design experiment with twelve participants. Chapter 2 belongs to conceptual system architecture, while chapter 3 and chapter 4 belong to empirical studies. All the parts are organized to realize the purpose of using MR technology to support participatory processes in community environment improvement.
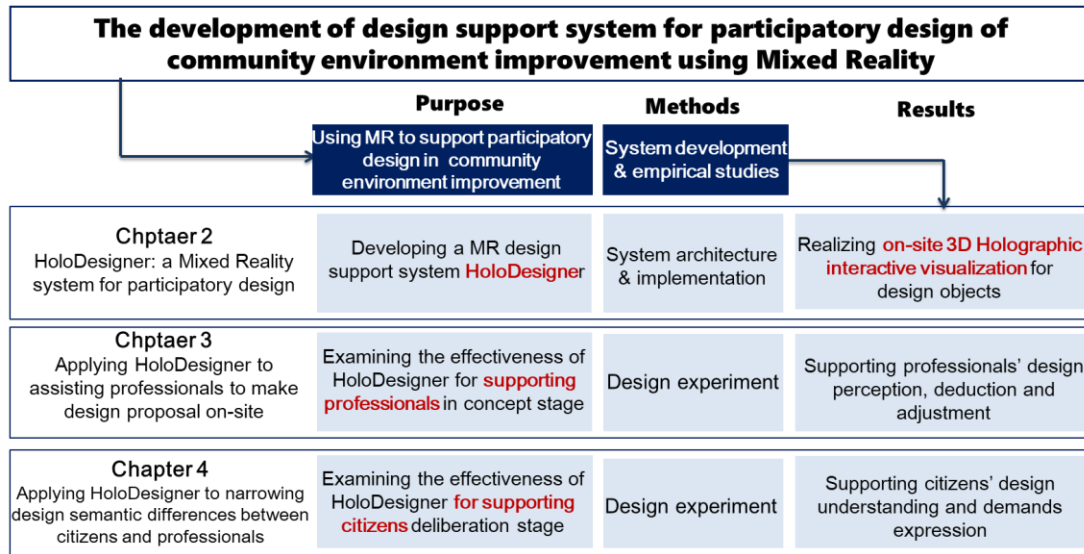
Fig. 1.7. The organization of the dissertation.

1.6.1 HoloDesigner: A Mixed Reality (MR) system for participatory design

Chapter 2 proposes a conceptual framework of the MR design support system. Participatory design has been consistently encouraged in community planning and design since the 1960s. However, this work was full of challenges because the current participatory design support systems could hardly bring virtual 3D design models to the actual community environment for intuitive interactive visualization. To cope with the challenges, we used MR technology to design and implement a design support system named HoloDesigner. In this chapter, we described the development process and core components of HoloDesigner. Also, we demonstrated its main workflow and functionalities. The results suggested that HoloDesigner could successfully realize on-site 3D visualization and real-time interactions for the virtual 3D models in the real community environment. This work has been published in the Automation in Construction (SCI, IF=7.7); Volume 129 in 2021.

1.6.2 Applying HoloDesigner to assisting professionals in making design proposals on-site

Chapter 3 examines the effectiveness of HoloDesigner for supporting professionals in the design concept stage. Specifically, we invited sixteen participants

to participate in an on-site design experiment at a typical community environment improvement scene. In this experiment, participants were required to perceive the community environment, make preliminary design deductions, and design adjustments on-site using HoloDesigner. Interviews and questionnaires were used to evaluate its effectiveness. The experimental results showed that HoloDesigner could provide professionals (especially those with weak design experience) with intuitive design perception, accurate design deduction, and convenient design adjustments, thus effectively assisting them in making design proposals on-site in the design concept stage. This work has been published in the journal Applied Science (SCI, IF=2.679); Volume 11 Issue 7 in 2021.

1.6.3 Applying HoloDesigner to narrowing design semantic differences between citizens and professionals

Chapter 4 validates that HoloDesigner can narrow the semantic differences between citizens and professionals in the deliberation process. To be specific, we recruited twelve participants (lay people) to take part in a design experiment for a typical campus community public space. In this experiment, participants were required to use HoloDesigner to visualize and understand the professional design proposal first and then make real-time design adjustments through HoloDesigner to express their design demands. Interviews and questionnaires were also used to examine the effectiveness. The results suggested the most participants could understand accurately the professional design proposal proposed by the design team through the intuitive 3D visualization of HoloDesigner. Meanwhile, most respondents could clearly convey their design demands to the design team by adjusting the design proposal in real-time using HoloDesigner. This work has been published in Proceedings of the 39th eCAADe Conference; Volume 1 in 2021.

Chapter 2. HoloDesigner：A Mixed Reality (MR) system for participatory design

2.1 Introduction

2.1.1 Research background

Participatory design has been consistently advocated in architectural design and urban planning fields since the 1960s (Lynch, 1960). Citizens and professionals are always encouraged and invited to sit together to make community environmental design proposals (Healey, 1997). This design method provides more opportunities for the citizens and professionals to understand the design environment, make design communication and finally reach a consensus

However, practicing such participatory design is full of challenges. Some professional design documents (like sketches, paper, and texts) are always used in the design concept and deliberation stages during the participatory design process (Schubert et al., 2015). Even for some professionals, it is difficult to relate and imagine these abstract documents in the real community environment intuitively because of the lack of effective tools, let alone the citizens who are not familiar with the professional design documents (Skov et al., 2013).

2.1.2 Related works

Recent computer graphic technology Mixed Reality (MR) could create a mixed visualization environment where virtual and real objects could co-exist in real-time (Milgram & Kishino, 1994). As a result, MR shows the possibility to develop a design support system to realize 3D visualization and real-time interaction for virtual design objects.

The earliest discovery can go back to the 1990s. Feiner, Webster, Krueger, MacIntyre, and Keller (1995) were the first to use MR technology in urban and

architectural design. They combined mobile computing technologies to develop an MR design support system, "Architect Anatomy". It could support users to visualize virtual design elements overlaying on the real building (Feiner et al., 1995). Although the single visualization function was limited in the lab, "Architect Anatomy" showed it would be promising for MR supporting participatory design in the future.

Subsequently, in order to realize design interaction and enrich functions, the design table-top began to be developed as the primary MR system to support participatory design. The design table-top universally integrated some complicated hardware such as physical tabletop, projection, camera, and external displays (Oksman et al., 2014). Typically, URP and Luminous Table realized real-time environmental analysis and design sketches inputting on the table-top surface in the MR environment (Underkoffler & Ishii, 1999; Ishii et al., 2002). However, they used physical models that must be prepared in advance and unable to adjust according to the specific requirements. So the following works began to try 3D digital models. For example, Sketchand+ utilized a digitizer tablet as the inputting interface to create 3D digital models viewed by the head-mounted display (HMD) (Seichter, 2003). ARTHUR, the more advanced MR participatory table-top, firstly provided users with gesture control to edit 3D design models from the first-person view (Broll et al., 2004; Schieck et al., 2005; Wang, 2013). Nevertheless, these MR participatory design table-tops always were blamed for never immerse 3D virtual design models in the real community environment for design interaction (Schubert et al., 2015).

To echo the real environment, an on-site physical enclosing system MR Tent came up. It brought the technologies previously available only in lab settings to the real community scene (Maquil et al., 2009). The following MR application, Urban Sketcher, created an on-site sketch inputting approach for the MR Tent (Sareika & Schmalstieg, 2007). However, this MR Tent contained many hardware devices and complex

installation and commissioning (Sareika, 2010). In addition, the fixed webcam limited users' viewpoints to visualize the MR scene (Schubert et al., 2015).

To address these limitations, MR design support system began to use mobile hardware devices. In particular, the recent smartphone equipped richer functionalities and became more portable (Oksman et al., 2014; Gill & Lange, 2015). The early MR design systems using the smartphone primarily paid attention to helping the public to view the possible 3D design objects at the specific design site (Allen et al., 2011). As the limited design functions, the early MR design support system could hardly achieve real-time design adjustments for the 3D design objects, thus not supporting users to express their design demands clearly (Schubert et al., 2015). Skov et al. (2013) proposed ArchiLens on the smartphone. This MR design support system could support users make real-time design adjustments for the possible 3D design objects on-site. Nevertheless, the 2D screen display based on the smartphone could scarcely realize immersive design perception (Wang, Chen, & Chen, 2018), and the rough tangible interaction could hardly support accurate design manipulation (Chi et al., 2013). As stuck at the limited hardware performance, few MR participatory design systems on mobile devices could support participatory design effectively.

With recent technology leaps, more advanced MR hardware devices have come up, especially for Microsoft HoloLens. It is a pair of wearable holographic glasses with a central processing unit (CPU), a graphics processing unit (GPU), and a holographic processing unit (HPU), allowing 3D visualization of holograms and immersive interactive experience in the MR environment (Microsoft, 2019). Microsoft HoloLens, as an MR hardware device, has been successfully applied into the medical field for 3D visualization-aid surgery (Agten et al., 2018; Brun et al., 2018; Deib et al., 2018; Incekara, Smits, Dirven, & Vincent, 2018; Tepper et al., 2017), safe pathological data analysis without direct physical contact (Affolter, Eggert, Sieberth, Thali, & Ebert,

2019; Hanna, Ahmed, Nine, Prajapati, & Pantanowitz, 2018; Jang et al., 2018), real-time interactive telemedicine (Gibby, Swenson, Cvetko, Rao, & Javan, 2019; Sirilak & Muneesawang, 2018; S. Wang et al., 2018); the educational field for the holographic simulation of real skill training scene (National Aeronautics and Space Administration [NASA], 2016; Mahmood et al., 2018; Yilmaz & Goktas, 2017); the exhibition field for interactive hearing or visual navigation (Hammadya & Ma, 2018; Pollalis, Fahnbulleh, Tynes, & Shaer, 2017); the geography fields for 3D viewing and sharing of GIS data (Wang et al., 2018); and others. Although rarely involved in the urban planning field by now, the technical characteristics presented by Microsoft HoloLens, like 3D visual display, unique interaction mode, and spatial depth perception, bring the possibilities for further improving the MR design support system for participatory design.

2.1.3 Research objective

Therefore, this research aims to use MR technology to develop a new design support system for participatory design. This new MR design support system is planned to realize 3D visualizations of design objects, offering immersive design perception for users making design proposals on-site. Furthermore, it considers providing real-time interaction possibilities for users making design adjustments and expressing design demands.

2.2 Methods

To achieve the research objective, we designed and developed a new MR design support system called HoloDesigner.

2.2.1 System design

The conceived HoloDesigner is an MR application software on Microsoft HoloLens. At present, there are already some related application software in the

Microsoft HoloLens platform. Generally, they can realize holographic visualization and essential control for virtual 3D models.

However, these application software cannot support participatory design effectively. First, not using the unique spatial mapping, they can hardly provide accurate spatial depth perception for users. Second, lacking rich design functions, they cannot assist users in making accurate design judgments and deductions. Third, lacking sufficient background maintenance, these application software ran slowly with the laggy gesture manipulation and holographic display (Affolter et al., 2019) and even crashed unexpectedly sometimes (Peterson et al., 2020).

Therefore, we can only inherit suitable partial functions (like object manipulation based on gesture and gaze) from the existing application software for supporting participatory design. Subsequently, we add some essential design functions (like material selection and distance measurement). In addition, we make the data transmission protocol and use cloud storage. The concept architecture of HoloDesigner is shown in Fig. 2.1.
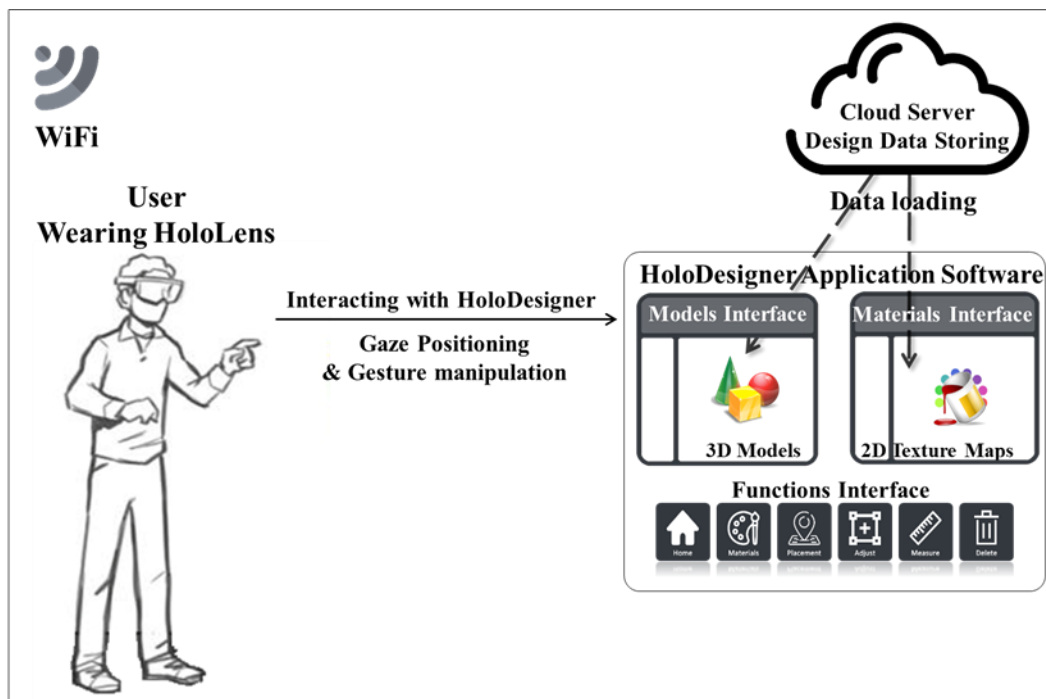
Fig. 2.1. Concept design of HoloDesigner.

HoloDesigner is planned to run in a WiFi environment. Design data (containing 3D models and 2D materials) were planned to load from a cloud server. We prepared three interactive interfaces for HoloDesigner, the models interface for loading 3D models, the materials interface for loading 2D materials pictures, the functions interface for offering several essential design functions. These design functions contain model adjustment (moving, rotating, scaling), model placement, model materials selection, model deletion, and distance measurement. In addition, the particular interaction depending on gaze and gesture from Microsoft HoloLens is ready to be introduced for users' control. Meanwhile, the creative physical contact between the virtual objects and the real environment also is planned to be realized through the unique spatial mapping of Microsoft HoloLens.

2.2.2 MR system development

Referring to the current application software development methods on the Microsoft HoloLens platform (Hammadya & Ma, 2018; Wang et al., 2018), we develop HoloDesigner through three primary steps on the personal computer (Fig. 2.2): Assets Creation; MR Application Software Development; and MR Application Software Deployment.
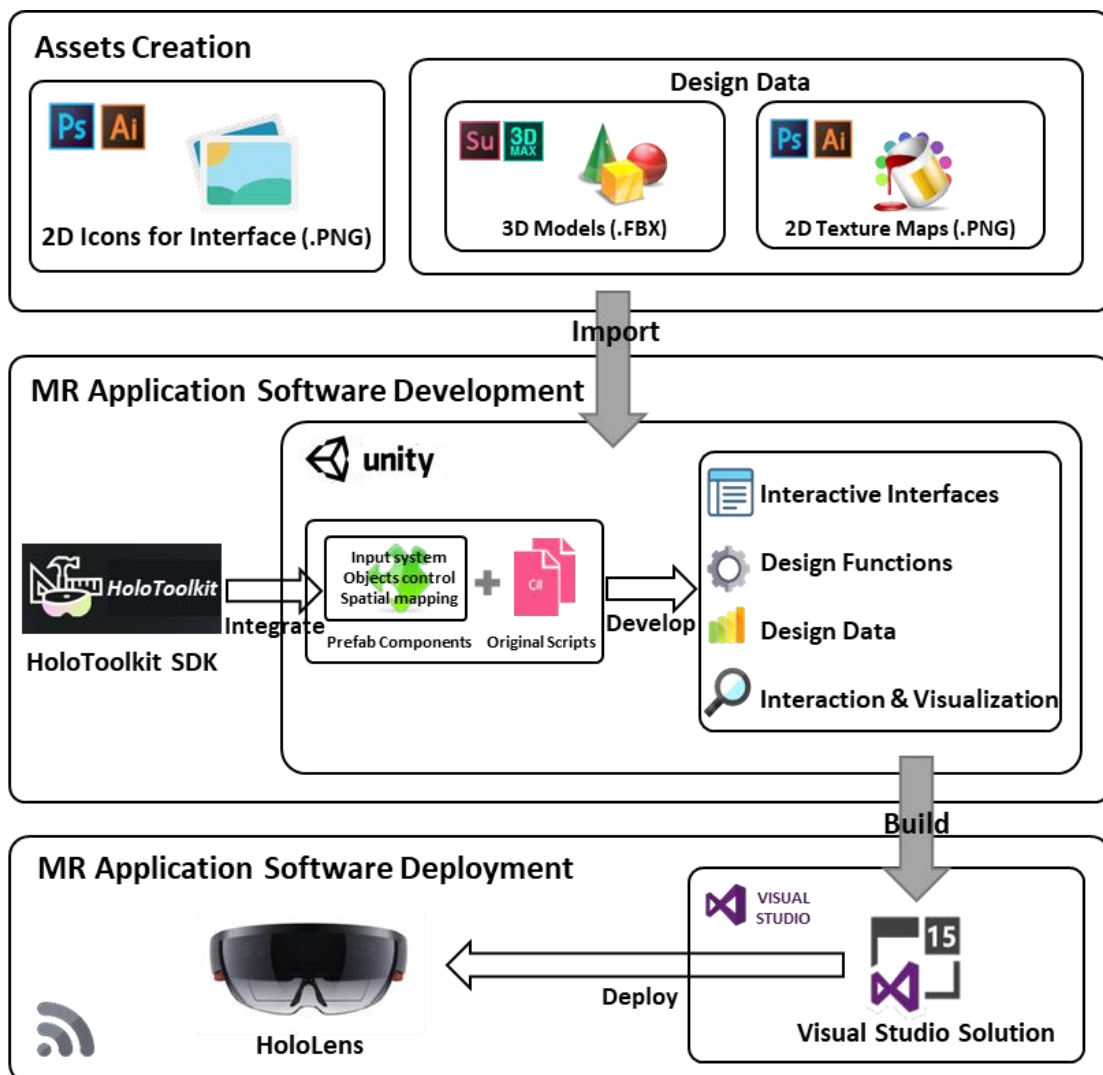
Fig. 2.2. Development Process of HoloDesigner.

2.2.2.1 Assets creation

For HoloDesigner, assets contain two parts: design data (3D models and 2D materials) for potential design objects and 2D pictures for the following interfaces. The

edition of the former is discussed in the later sections. The latter is made by some picture-edited tool like Photoshop. Moreover, all the prepared 2D pictures are saved in PNG format and ready to be imported into Unity 3D for the creation of the interfaces.

2.2.2.2 MR application software development

The game engine Unity 3D was used as the core platform to develop the MR application software in this research. We also used the HoloToolkit Software Development Kit (SDK), an open resource library providing the developer with prefab class scripts and components (Microsoft, 2018). All the coding works in the development were done in C# language. Specifically, this MR application software development experienced four important processes: making interactive interfaces, developing design functions, implementing design data, and establishing interaction and visualization.

1) Creating interactive interfaces

Interactive interfaces, as the fundamental element of HoloDesigner, include the models interface, the materials interface, and the functions interface. They are created, modified, and attached to the 2D icons previously prepared by UGUI (an interface-building tool in Unity 3D). The edited interactive interfaces are stored as local resources and linked with their respective "setting" classes (ModelsPage, MaterialPage, and FunctionsPage), which are found and read by the matching "controlling" classes (ModelsPageController, MaterialsPageController, and FunctionsPageController).
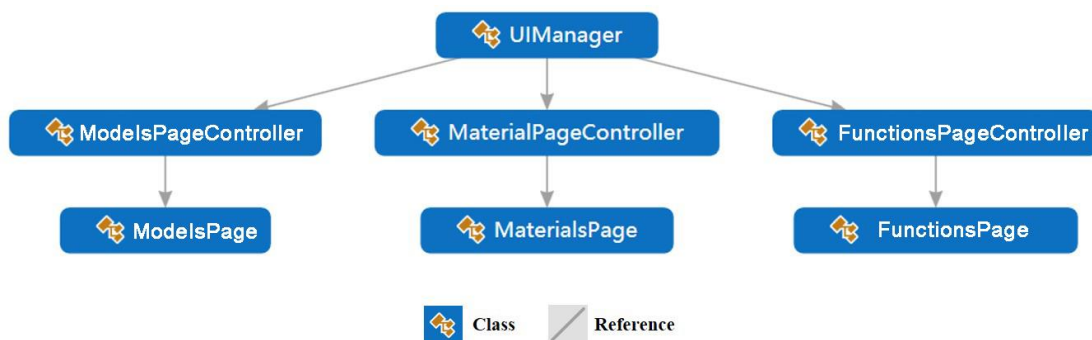
Fig. 2.3. Code map for loading the interactive interfaces.

Subsequently, the three interfaces controlling class are referenced, enumerated, and finally written into the UIManager class, which manages all interfaces, to load the three interactive interfaces (Fig. 2.3).

2）Developing design functions

Design functions were another essential part of our MR application software, which would provide potential design behaviors for real-time interaction. In HoloDesigner, we developed the following design functions: model adjustment, model placement, model deletion, spatial distance measurement, and model materials selection. The first three functions were realized by referencing the prefab scripts from HoloToolkit SDK more or less. The latter two functions were achieved by mainly building original code in Unity 3D.

Specifically, model adjustment function references the object control component from HoloToolkit SDK (Fig. 2.4). The BoundingBox class principally provides a prefab adjustable bounding box for potential 3D models. The ShowBoundingBoxGizmoHandle class mainly takes charge of getting potential manipulation events and returning the updated values to Class ShowBoundingBoxRig. Finally, the ShowBoundingBoxRig class references the BoundingBox class to achieve real-time 3D model adjustments.
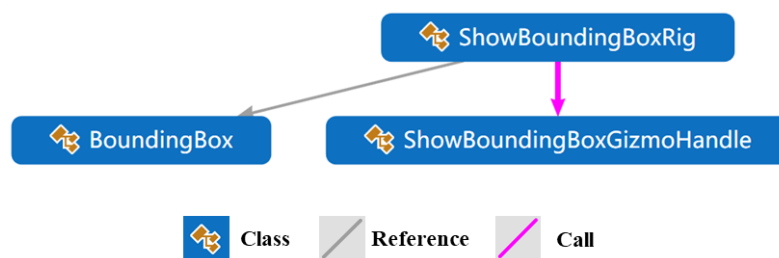
Fig. 2.4. Code map of model adjustment.

The model placement function mainly references the prefab Spatial mapping component from Holotoolkit SDK (Fig. 2.5). More concretely, the SpatialMappingObserver class instantiates a prefab Surface Observer to scan the

physical environments and creates digital meshes, which are transmitted to the SpatialMappingMannager class for further rendering and filtering. Then, the processed digital triangle meshes are converted to planes by the SurfaceMeshestoPlanes class. Finally, the Placeable class gets the updated plane data by referencing the SpatialMappingMannager class and calculates the possibilities for placing potential 3D models by the method ValidatePlacement().

The function model deletion function always logically followed follows the function model placement functionlogically. Hence, we created a method OnDestoroy() in the class Placeable class, which called calls the prefab method destroy() from the Unity Engine Core Module, for to deleting delete potential 3D models (Fig. 2.5).
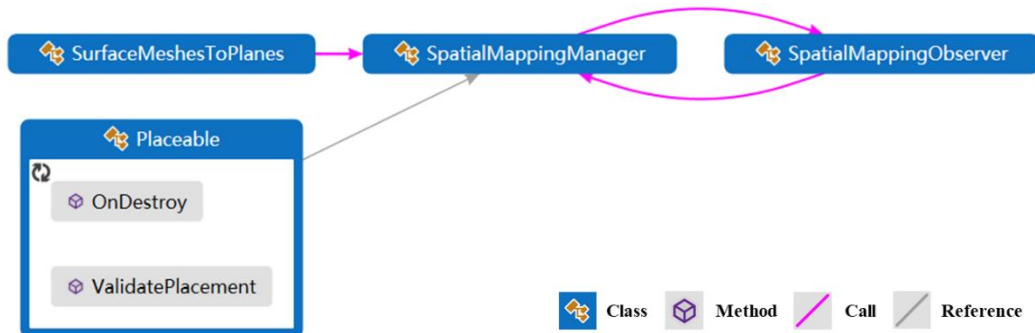
Fig. 2.5. Code map of model placement and model deletion.

To develop the spatial distance measurement function, we wrote the Point class with a method Point() to get the spatial properties of an arbitrary point. After receiving potential control orders, the LineManager class uses the method AddPoint() to call the Point class to get the spatial vector of each point to calculate distances. The calculation results for distance is written into the MeasureManager class for further management (Fig. 2.6).
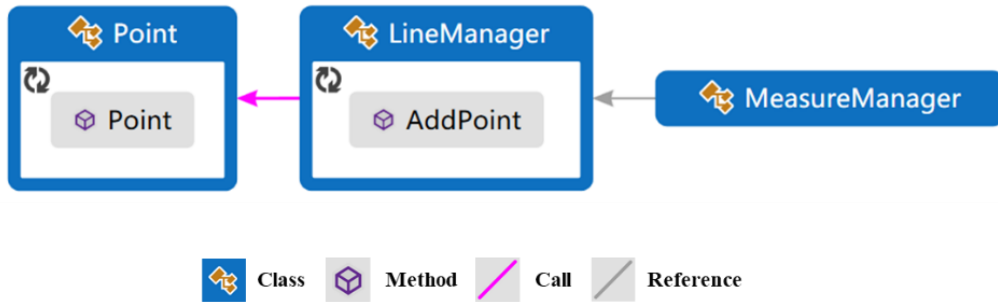
Fig. 2.6. Code map of spatial distance measurement.

The materials selection function mainly involves interfaces switching, from the functions interface to the materials interface. Furthermore, the MaterialsPageController class references the EditorView class to record potential control orders, and the updated values are returned to the EditorMachine class. Through calling the EditorMachine class, the MaterialsPageController class gets the new orders and reads materials interface information to switch the interface (Fig. 2.7). Then, the model materials selection function is achieved, followed by design data implementation, and establishing interactivity and visualizations.
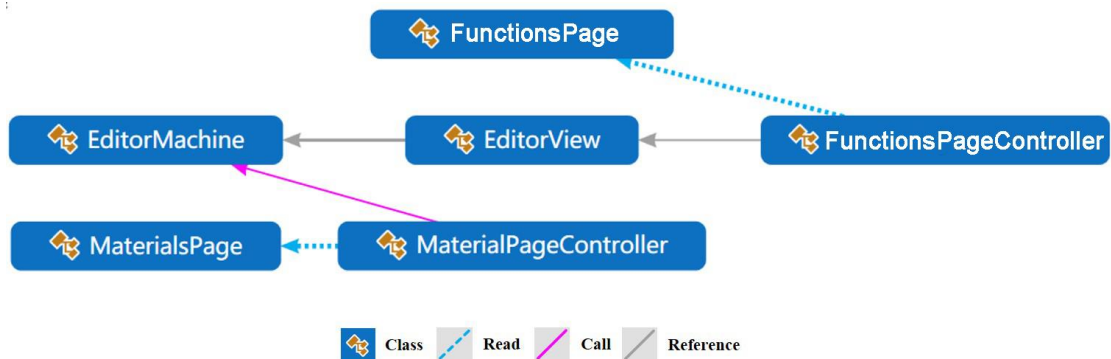
Fig. 2.7. Code map for switching to the materials interface.

After developing the design functions, we linked the edited function scripts to the functions interface. Furthermore, we wrote five corresponding function state classes (AdjustState, PlaceState, DestroyState, MeasureState, MaterialState) for functions to be used after implementing design data, and establishing interactivity and visualizations.

3）Implementing design data
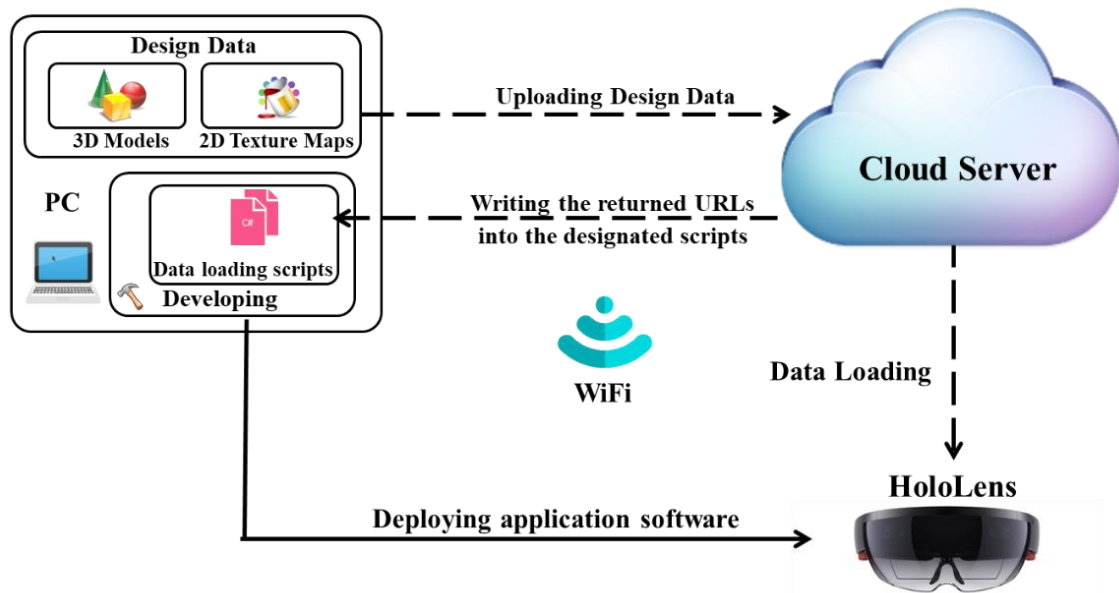
Fig. 2.8. Design data implementation approach

In development, data implementation is also a critical part. Design data are loaded from the cloud server according to our concept architecture (Fig. 2.8). In the MR application software, design data primarily includes 3D models and 2D materials. Universally, 3D models are made in models-creating software like Google SketchUp, and 2D materials are edited in graphics-creating software like Adobe Photoshop. Subsequently, we transmit the prepared design data to the designated cloud server for getting the corresponding Uniform Resource Locators (URLs). Then, we write the URLs in the related data-loading scripts to implement the design data.
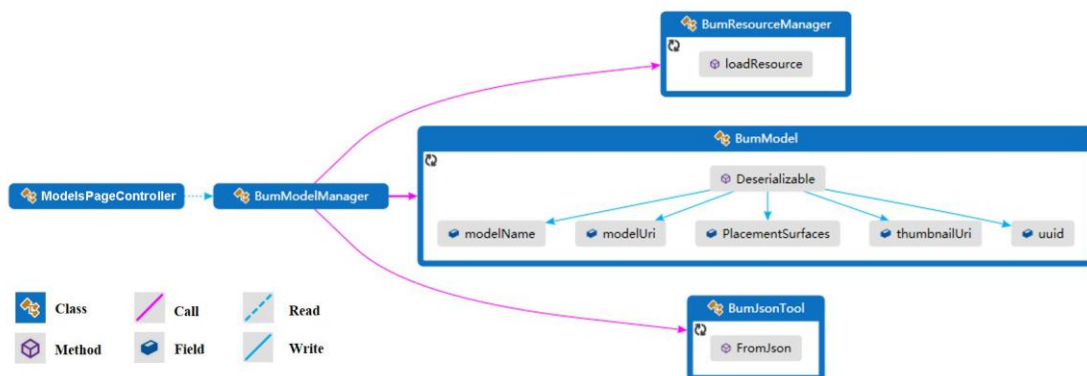
Fig. 2.9. Code map of 3D models implementation.

Taking the 3D models, for example, the BumModelManager class for data loading converts the data table list into the recognized information by calling the method FromJson() of the class BumJsonTool. Then, the BumModelManager class lists all the information of the 3D models and finds their store path by calling the method Deserialization() of the BumModel class. Following the path, the BumModelManager class gets the 3D models from the cloud server by calling method loadResource() of the BumResourceMananger class, which are read by the ModelsPageController class for data loading (Fig. 2.9).

4）Establishing interactivity and visualization

At this point, the critical work is to establish real-time interactivity among the user, the interfaces, the functions, and the design data, followed by archiving the visualizations. As shown in Fig. 2.10, first, the prefab input system component (containing the GazeManager class and the GestureInteractive class) from HoloToolkit SDK is referenced to prompt gaze and gesture input. Secondly, the GazeMoveState class handles potential gesture and gaze events. The updated values are returned to the InputState class for further recording and management. Then, the interface controlling classes reference the InputState class to get the input orders and implement corresponding interface controls by gaze and gesture. Similarly, the model controlling classes call the InputState class to get input orders to control potential 3D models. When the input orders refer to the function's usage, the corresponding function state classes call the InputState class to add function events and execute the concrete design

behaviors. Finally, the ModelView class updates and visualizes the real-time interaction process.
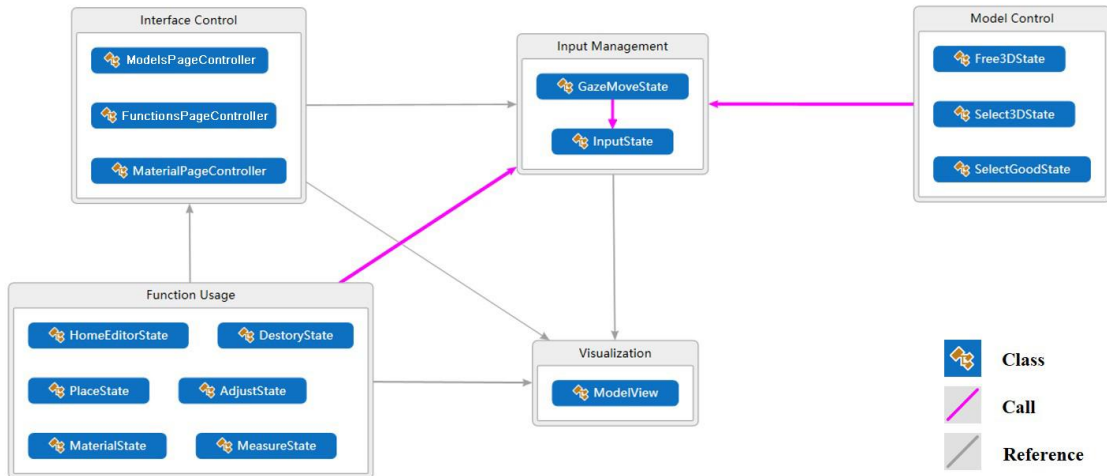
Fig. 2.10. Code map of establishing interactivity and visualization.

Subsequently, with the compilation of source code, the MR application software is built and exported from Unity 3D as a Visual Studio Solution for deployment.

2.2.2.3 MR application software deployment

Microsoft Visual Studio was used as the primary software to implement this MR application software deployment in this process. Concretely, Microsoft HoloLens and Personal Computer (PC) needed to join the same wireless network to avoid access errors led by the limited network protocol. Through pairing IP addresses, Microsoft HoloLens connected to Microsoft Visual Studio as a remote device. Subsequently, we performed debug to deploy the MR software application to HoloLens.

So far, the new MR design support system HoloDesigner has been developed successfully.

2.3 Results

2.3.1 The workflow of HoloDesigner
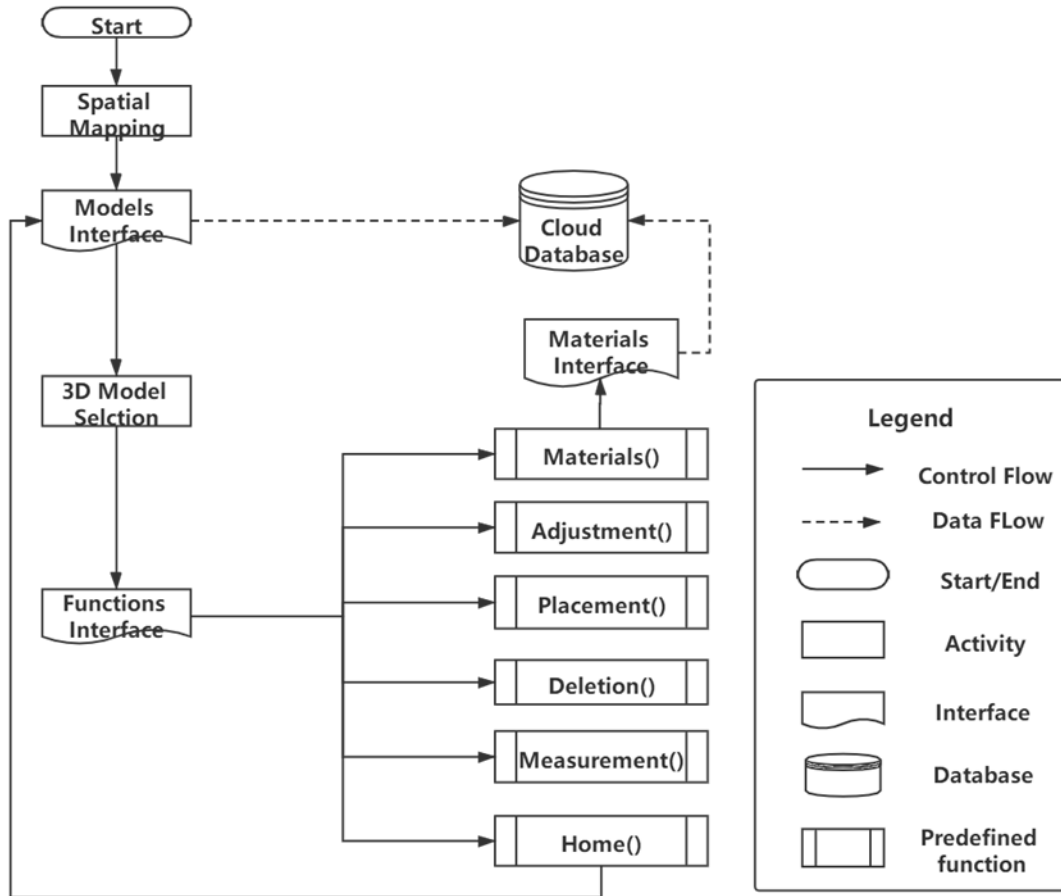
Fig. 2.11. The workflow of HoloDesigner.

From Fig. 2.11, we can see the primary work process of HoloDesigner. When HoloDesigner started up, the spatial mapping would first run to scan the physic community environment and build the digital built-in triangulation meshes (Fig. 2.12). Subsequently, the models interface, loaded with the prepared 3D street furniture models from the cloud database, would come up in the MR scene (Fig. 2.13). At the same time, with the induction of prefab interaction mode, users were able to select suitable design objects by gaze and gesture control. With gaze positioning and gesture-clicking the selected design objects, the functions interface, including six holographic buttons (Placement, Adjustment, Materials, Delete, Measurement, and Home), appeared (Fig.

2.14). Thus, users could call appropriate design functions to make real-time design deductions according to community environmental details, thus finished preliminary design. In addition, when users clicked the function button Materials, the materials interface with the prepared 2D materials pictures loaded from the cloud would also come up for the following manipulation (Fig. 2.15).
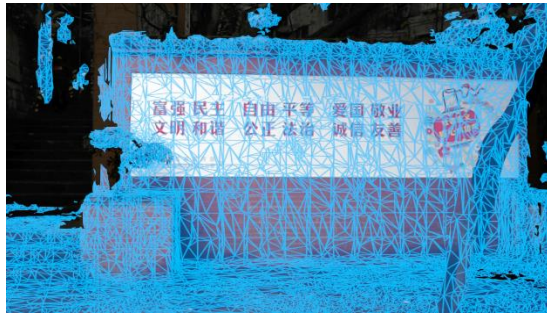
Fig. 2.12. Spatial mapping.
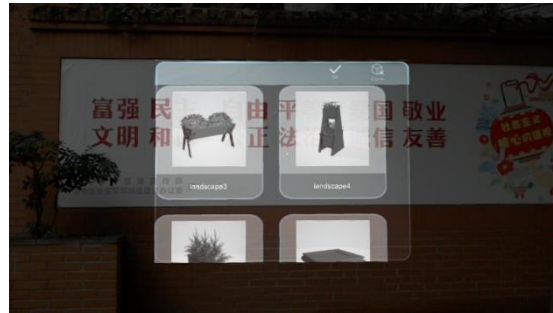
Fig. 2.13. Models interface.
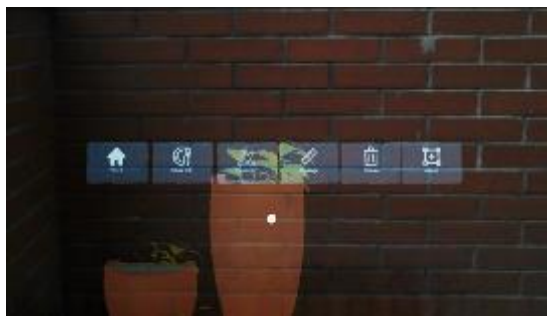
Fig. 2.14. Functions interface.

Fig. 2.15. Materials interface.

2.3.2 On-site 3D visualization
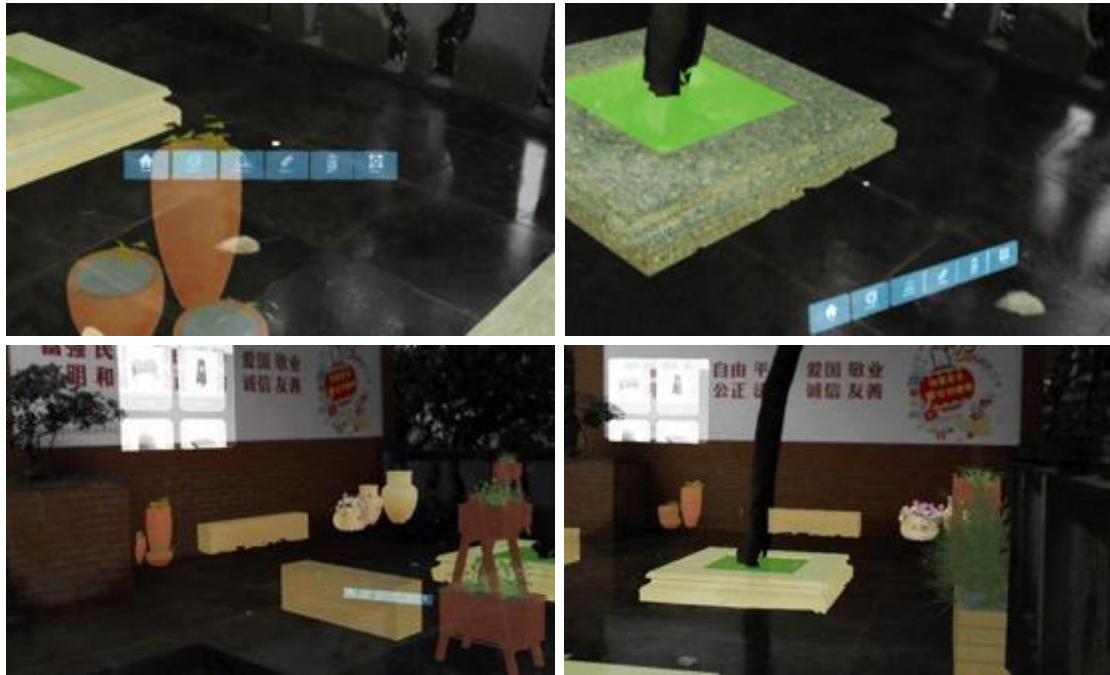
Fig. 2.16. On-site 3D visualization through HoloDesigner.

We demonstrated that the prepared 3D design objects could be immersed in the actual community scene for on-site visualization using HoloDesigner (Fig. 2.16). In addition, this was a 3D visualization, which supported explicit materials display as well as the stereoscopic form and exact scale rendering (Fig. 2.16). Besides, this visualization was able to allow users to move freely at the design site to understand the environmental details and select the appropriate viewing angle according to different design demands (Fig. 2.16).

2.3.3 Real-time interactions

(a)   (b)
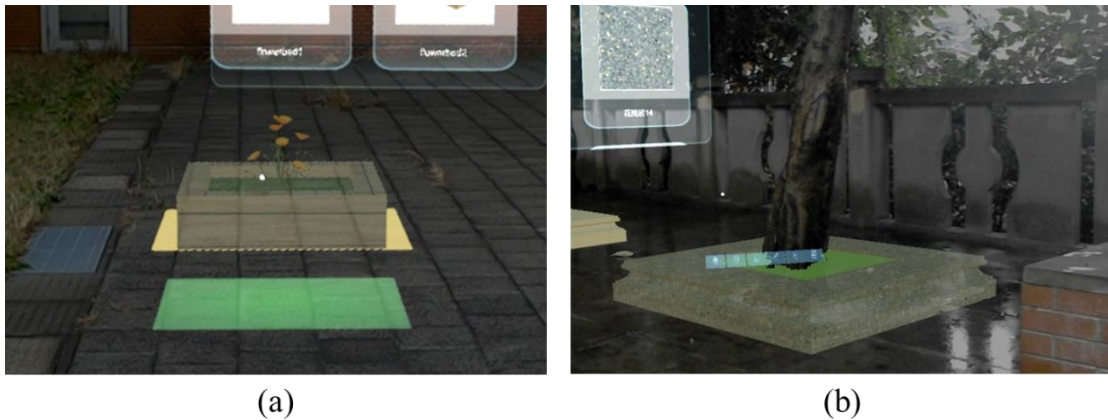
Fig. 2.17. Real-time physical contact between the virtual 3D model and the real surrounding environment; (a) the virtual 3D flower box model placed on the real community park floor; (b) real spatial occlusion between the 3D Tree pool model and the real tree.

First, we could see that this MR system could support the real-time physical collision between the virtual design objects and the real community scene. More precisely, this physical collision relied on the blue digital meshes made by the unique spatial mapping feature from the hardware itself. These digital meshes allowed rigid contact, thus supporting the placement of the virtual design objects on the floor of the real community scene as Fig. 2.17(a) (the green shadow suggesting available placement). Besides, the digital mesh reflected the real spatial relationship, thus displaying physical occlusion between the real community scene and the virtual design objects, like the real tree and the virtual 3D tree pool model in Fig. 2.17(b).

Fig. 2.18. Gaze positioning cursor and controlling the object with gestures.

Second, we could see that HoloDesigner was able to support real-time manipulation. In this regard, this control mainly depended on gaze and gesture. Furthermore, as Fig. 2.18 shows, gaze determined the position of the cursor, and gesture offered the possibility to control objects. The controlling objects contain the virtual design objects as well as the interactive interfaces. As a result, using gaze positing and gesture controlling, users could change the position and scale of the interfaces and choose suitable design objects. Additionally, users could measure the spatial distance accurately, add or remove corresponding design objects, and set suitable physical design parameters (like position, scale, angle, and materials) for them (Fig. 2.19). Users thus realized real-time design deduction and adjustments using HoloDesigner under the community environmental details.
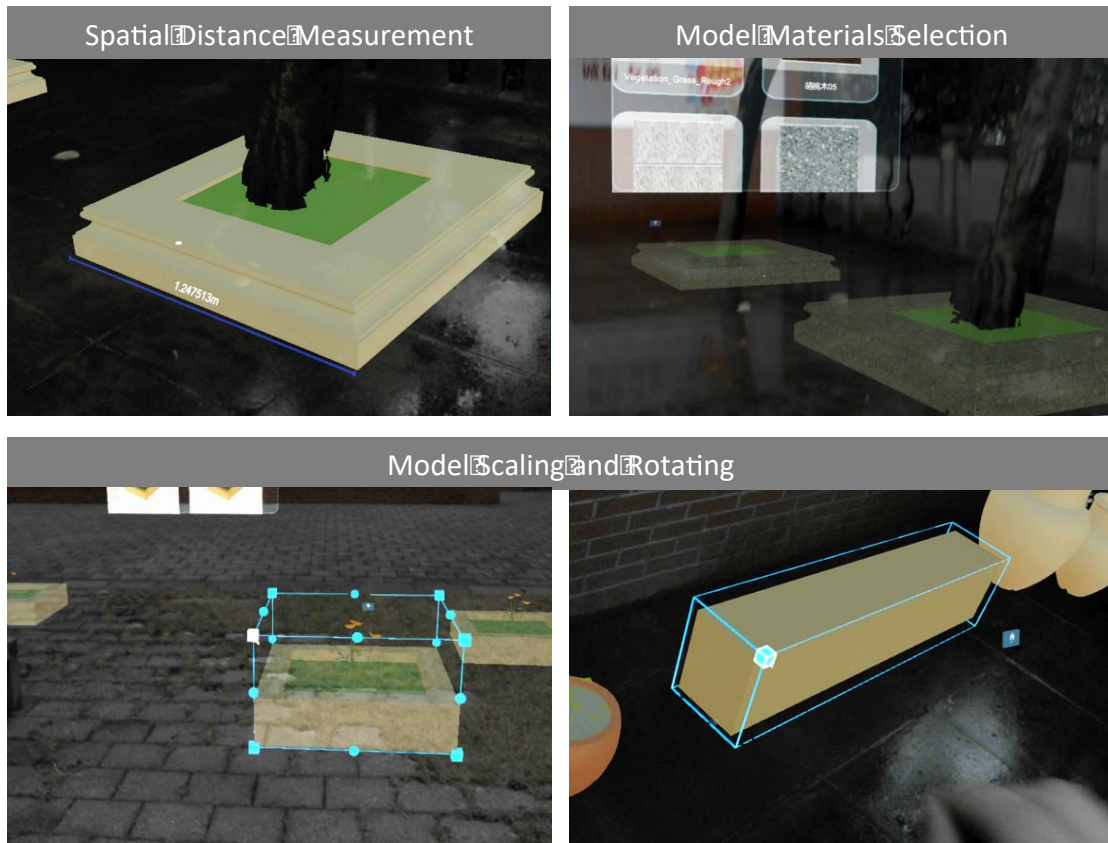
Fig. 2.19. Real-time control through HoloDesigner.

2.4 Discussion

We have shown that this MR system HoloDesigner realizes on-site 3D visualization as well as real-time design interactions for virtual design objects. In brief, our results show that HoloDesigner has enormous potentials to support participatory design effectively.

To be specific, from the research results, we can see HoloDesinger could support users in visualizing the virtual 3D design objects in the real community scene instead of imaging them in the brain. Moreover, this visualization does not rely on the 2D screen display like the traditional MR design support systems on mobile devices. The unique 3D holographic rendering offered precise spatial depth perception. In addition, this visualization is not limited to a single scene and a fixed view caused by the complex physical installations. Considering the mobility of Microsoft HoloLens, users can perceive the community environmental details and visualize their design objects on-site from different angles using HoloDesigner. In a word, this 3D holographic visualization gives the users an intuitive perception of understanding the professional design proposal.

At the same time, we can see that HoloDesigner redefines the interaction mode of MR design support systems. Gaze positioning and gesture manipulation do not depend on stiff physical media (such as touch pen, panel, or screen) of conventional MR design support systems using the tangible user interface. It gives users more flexible design manipulation. Furthermore, instead of visual overlaying the virtual 3D design objects and the real community environment through a 2D screen, HoloDesigner achieves 3D physical interaction. This interaction can realize real contact and occlusion between virtual 3D objects and the real physical environment. The unique interaction mode provides users with more possibilities to express their design demands clearly.
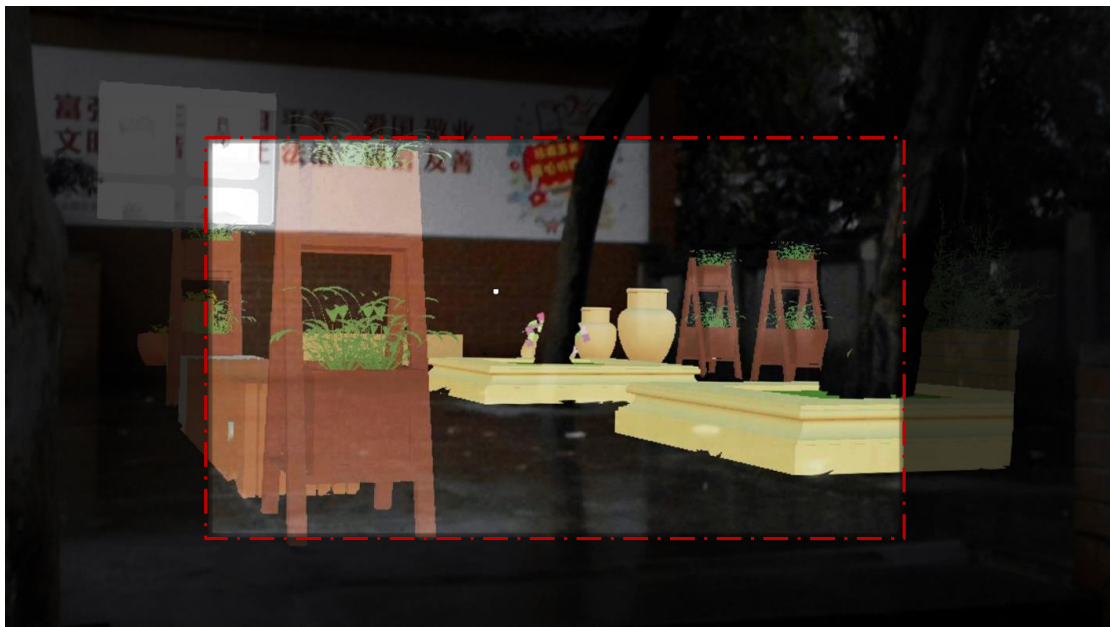
Fig. 2.20. Field of view (FOV) of HoloDesigner.

However, there are still some limitations in this new MR design support system, HoloDesigner. First, the field of view (FOV) of HoloDesigner is very narrow, as the red dashed box in Fig. 2.20. It is hard for users to see their design objects in the whole MR scene. It is mainly attributed to the limited hardware level. Therefore the manufacturer has been committed to improving this deficiency and made a relatively larger FOV with the recently upgraded version (Microsoft, 2019). Second, the present control based on gaze and gesture is still relatively rough, spending users much time manipulating design

objects accurately. This disadvantage could be blamed for the prefab interaction kit not giving rich manipulation behaviors. It would be improved by supplementing some related functions like accurate object capture or design parameter input. Third, the tedious data preparation process is quite complex for users. It includes the edition, adjustment, and uploading of design data and complicated debugging across the multi-software platform, such as SketchUp, Adobe Photoshop, Unity 3D, and Microsoft Visual Studio. Regarding the current function architecture of HoloDesigner, this tedious data preparation process is difficult to simplify. By grasping the corresponding software usage skills proficiently, users can make the data preparation smoothly.

This research has designed and implemented a new MR design system, HoloDesigner, to support participatory design. We have demonstrated its main workflow and immediate improvements in on-site visualizations and real-time interactions with 3D design objects. The results suggest that our system has the potentials to facilitate design participation effectively in community environment improvement.

In the future, we will continue to improve this MR design support system. In addition, we intend to test its effectiveness in different stages of participatory design in community environment improvement through design experiments.

Chapter 3. Applying HoloDesigner to assisting professionals in making design proposals on-site

3.1 Introduction

3.1.1 Research background

Community environment improvement involves more diverse stakeholders and faces more complex urban built environments than conventional urban planning and design (Zhang et al., 2013). Furthermore, the present community built environment universally includes several trivial and complicated details like buildings, public facilities, street furniture, landscapes, and others, which always are hard to be measured and integrated into traditional design drawings accurately, thus bringing challenges for professionals making design perception, deduction, and adjustments (Huang et al., 2014). Consequently, professionals gradually have chosen to come back to the community design scene to deeply observe and understand the environmental details, thus making intuitive design perception, accurate design deduction, and convenient design adjustments on-site (Holl et al., 2006). Such on-site design methods derive from "back to the things themselves" of phenomenological movement (Husserl, 1936), which contributes to professionals perfectly immersing their design proposal into the community environment to evoke the "aura" of the space (Norberg-Schulz, 1979; Benjamin, 1968).

However, with the limitation of technological level, the present on-site design works of community environment improvement primarily depends on the professionals' visual imagination (Brolin, 1980; Holl, 1991), which is too abstract to control, thus hardly guaranteeing intuitive design perception and accurate design deduction, always incurring repetitive works (Skov et al., 2013).

3.1.2 Related works

Over the years, the rapidly developing Computer Graphics (CG) has brought numerous possibilities to address these limitations. In the 1990s, Virtual Reality (VR), the computer-generated imagery technology, began to be used to support urban planning and design (Pittman, 2012).

The early VR design support systems (likes CAVE, Geo wall, and Vision Dome) integrated several single hardware devices (likes 2D screen, sensor, personal computer (PC), head-mounted display (HMD), and inputting panel). They could render vivid and immersive virtual environments indoors, which had the possibility to support users' environmental perception and design concept (Chen & Schnabel, 2009). At the same time, in the immersive virtual environment, 3D virtual design objects could be generated for viewing (D'Souza et al., 2011). Subsequently, sound and animation had been added to this immersive virtual environment (Guo & Yang, 2013). The tangible interface offered the approach for users to interact with the immersive virtual environment (Gu et al., 2011; Portman et al., 2015). Nevertheless, the immersive virtual environment was totally separated from the real world, not offering the real spatial relationship and supporting accurate environmental perception (Kim & Dey, 2010). In addition, the creation of the models for the immersive virtual environments would take a large number of effort, which still could not achieve the whole details reduction (Schubert et al., 2015). Besides, the VR design support systems were universally contained some expensive and complex hardware that were always operated in professional labs and not available for most users (Lange, 2011; Portman et al., 2015).

Whereafter, the more advanced Augmented Reality (AR) technology was applied to urban planning and design fields to assist professionals in making on-site design perception, deduction and adjustment. AR can render the environments where virtual objects could be overlaid onto the real world (Wang et al., 2013). Depending on the

mobile device (like the smartphone and mobile tablet), AR could overlay the digital design objects onto the real environment (Allen et al., 2011; Gill & Lange, 2015).In addition, the mobile device could be the input interface, offering real-time design manipulation and supporting professionals to make convenient design deductions and adjustments (Skov et al., 2013). Meanwhile, with remote computer analysis, real-time environmental simulation (like wind, light, and heat) could be displayed in AR environments (Woodward & Hakkarainen, 2011; Olsson et al., 2012; Schubert et al., 2015). However, this display based on the 2D screen of the mobile device scarcely reflected the real spatial depth and relationship; thus, it was hard to assist professionals to acquire intuitive environmental perception even though they came back to the real design scene (Wang et al., 2018). Similarly, the input interface based on the 2D screen was narrow and stiff, which hardly provided professionals with flexible and accurate design manipulation (Chi et al., 2013).

The following Mixed Reality (MR) technology integrates the advantages of both VR and AR (Alizadehsalehia et al., 2020), which can merge the real and virtual world to produce new visual environments where real and virtual objects co-exist (Milgram & Kishino, 1994). With the rapid advances of technology, the advanced MR HMD Microsoft HoloLens (Microsoft, Redmond, WA) has come up, making MR technology available in some professional fields. Specifically, by now, MR has been used in the medical field for 3D visualization-aid surgery planning (Agten et al., 2018; Brun et al., 2018; Deib et al., 2018), the aerospace field for the simulation of the environments of space exploration (National Aeronautics and Space Administration [NASA], 2016; Mahmood et al., 2018), the tourism field for the interactive acoustic and visual navigation (Hammadya & Ma, 2018; Pollalis et al., 2017), the geography fields for 3D viewing and sharing of GIS data (Wang et al., 2018); and others. These successful discoveries show several critical technological features of MR, such as the 3D

holographic visualization, the natural interaction mode, and the spatial depth perception, which allows professionals to make intuitive design perception, accurate design deduction, and convenient design adjustments.

3.1.3 Research objective

This research intends to apply HoloDesigner to assist professionals in making intuitive design perception, accurate design deduction, and convenient design adjustment in the concept stage of participatory design. A design experiment for a typical community environment improvement scene with sixteen participants was performed to examine the effectiveness.

3.2 Materials and methods

3.2.1 MR design support system--HoloDesigner
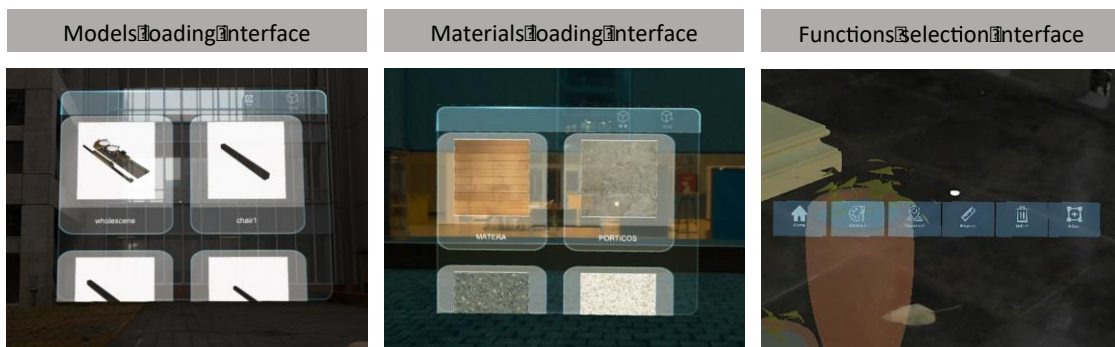
Fig. 3.1. The interactive interfaces of HoloDesigner.

HoloDesigner is an MR design support system on Microsoft HoloLens for participatory design. HoloDesigner was developed by our research team using the Unity 3D engine in C # language (the development details are in chapter 2), which mainly realize on-site 3D visualization and real-time interaction of design objects in the WiFi environment. As Fig. 3.1 shows, HoloDesigner has three interactive interfaces. In this regard, the three interfaces contain the models interface for loading 3D models, the materials interface for loading 2D materials pictures, the functions interface for offering several essential design functions. These design functions include model adjustment

(moving, rotating, scaling), model placement, model materials selection, model deletion, and distance measurement. Design data (containing 3D models and 2D materials) are loaded from a cloud server. In addition, the particular interaction depending on gaze and gesture from Microsoft HoloLens is ready to be introduced for users' control. Meanwhile, the creative physical contact between the virtual objects and the real environment also is planned to be realized through the unique spatial mapping of Microsoft HoloLens.

3.2.2 Case selection and data preparation

To examine the effectiveness of HoloDesigner for supporting participatory design, we selected a typical community environment improvement scene to carry out the following design experiment. This community environment improvement scene is located at Huafuxiang community of Yuzhong District in Chongqing city, China. It was designed preliminarily by the professional design group to supplement some street furniture according to the residents' demands and the environmental details (Fig. 3.2).

Fig. 3.2. The preliminary design proposal for a typical design scene.

The data preparation process primarily included the edition, uploading, and coding for the needed street furniture (like benches, tree pools, and flowerpots) models. Thus, as shown in Figure 3.3, we first created the alternative 3D models using Google Sketchup and corresponding 2D materials maps using Adobe Photoshop. Then we stored these edited 3D models and 2D materials maps in a cloud server and acquired the corresponding Uniform Resource Locators (URLs). Finally, we wrote these URLs in the designated data implementing script of the program assembly of HoloDesigner, thus completing the data preparation.
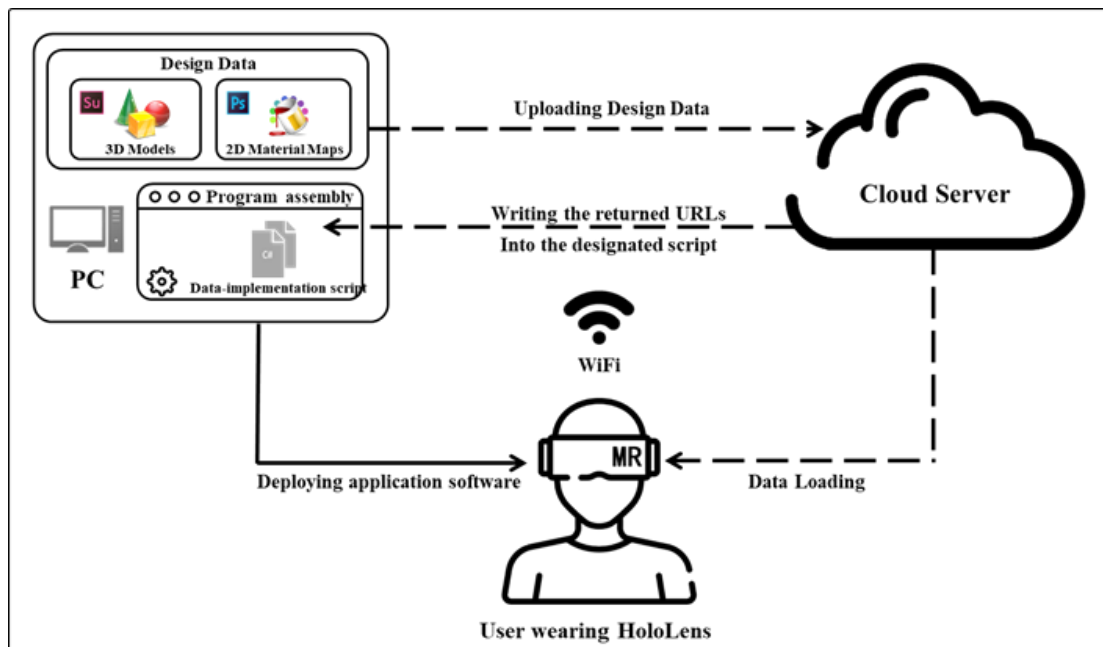
Fig. 3.3. The design data preparation process.

3.2.3 On-site design experiment

The experimental time was 2:00 PM-6:00 PM on December 11th, 2018. We invited sixteen participants (all of them are professionals) to participate in the design experiment at the selected community environment improvement scene based on the previous preparation. According to the research purpose, we evaluated the effectiveness of HoloDesigner for supporting professionals in the concept stage of participatory design from three aspects (intuitiveness, accuracy, and convenience) by interview and questionnaire.

3.2.3.1 Participants

The sixteen participants contained eight males and eight females, and all of them were designers from professional design institutions. Their age ranged from 24 to 47 years (Mean ± Standard deviation: 30.38 ± 7.18 years, Median: 27 years). Although only five of them ever had related MR technology usage experience, all the participants ever participated in related design practice of community environment improvement. Their design experience range was from 3 to 26 years (Mean ±Standard deviation: 9.25 ± 7.15 years, Median: 6.5 years), which contributed them to experiencing the differences brought from HoloDesigner clearly in this experiment.

In addition, the participants could be divided into three groups and two groups based on "design experience" and "MR usage experience," respectively. (Table 3.1, Table 3.2).

Table 3.1. MR usage experience groups.

	MR usage experience groups	
	With MR usage experience	Without MR usage experience
Participants	5	11

Table 3.2. Design experience groups.

	Design experience groups		
	1-10 Years	11-20 Years	21-30 Years
Participants	9	5	2

3.2.3.2 Experimental procedures
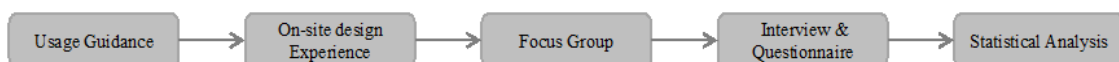
Fig. 3.4. The on-site experimental procedures.

Firstly, as shown in Fig. 3.4, we gave a usage instruction of HoloDesigner to each participant respectively. This process lasted approximately five to ten minutes, primarily including explanations for the interfaces and functions and the instructions for the gesture and gaze manipulation.

Fig. 3.5. Participants engaged in the on-site design experience.

Then, every participant used HoloDesigner to perform a ten-minute design experience upon the experimental requirements (Fig. 3.5). Concretely speaking, based on the preliminary design proposal for this scene, every participant selected the planned 3D street furniture models for the space from the cloud storage, and placed them for the appropriate position considering the accurate spatial relationship perception, then made the real-time adjustment for the design objects according to the environmental details and citizens' demands through calling the corresponding functions of the MR design support system (Fig. 3.6, Fig. 3.7).

Fig. 3.6. The 3D on-site visualization of the virtual design proposal using HoloDesigner.
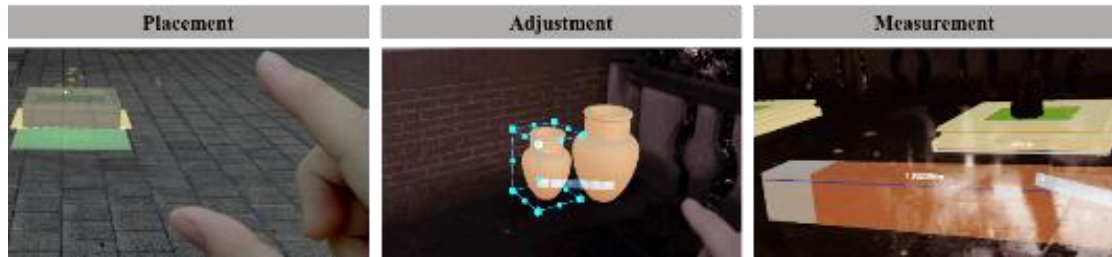
Fig. 3.7. The real-time control for the virtual design objects using HoloDesigner.

After the participants completed their design experience, we organized a focus group to discuss the influential factors for assist professionals in making design proposals on-site using HoloDesigner from three aspects (intuitiveness, accuracy, and convenience). Specifically speaking, we learned the improvements for design intuitiveness using HoloDesigner mainly referred to the realness of the physical environment, the verisimilitude of the virtual design objects, and the immersion of the MR environments. The improvements for design accuracy using HoloDesigner chiefly included design materials selection, design position judgment, and design size control. The improvements for design convenience using HoloDesigner primarily involved the comfort of HoloDesigner, the difficulty of HoloDesigner, and the control of HoloDesigner.

Thus, we designed a questionnaire in accordance with the results of the focus group, and all the main questions ranged on a five-point Likert scale (Fig. 3.8). Subsequently, we took an interview with each participant based on the questionnaire to examine the effectiveness of HoloDesigner.

On-site design experience using HoloDesigner

1 On-site design intuitiveness using HoloDesigner

1.1 The realness of the physical world in MR environments:

☐ 5 (Extremely real)　☐ 4 (Very real)　☐ 3 (Moderately real)　☐ 2 (Slightly real)

☐ 1 (Not at all)

1.2 The verisimilitude of the virtual design objects in MR environments:

☐ 5 (Extremely verisimilar)　☐ 4 (Very verisimilar)　☐ 3 (Moderately verisimilar)

☐ 2 (Slightly verisimilar)　☐ 1 (Not at all)

1.3 The immersion of the MR environments:

☐ 5 (Excellent)　☐ 4 (Very good)　☐ 3 (Good)　☐ 2 (Fair)　☐ 1 (Poor)

2 On-site design accuracy using HoloDesigner

2.1 The design materials selection using HoloDesigner:

☐ 5 (Extremely accurate)　☐ 4 (Very accurate)　☐ 3 (Moderately accurate)

☐ 2 (Slightly accurate)　☐ 1 (Not at all)

2.2 The design position judgment using HoloDesigner:

☐ 5 (Extremely accurate)　☐ 4 (Very accurate)　☐ 3 (Moderately accurate)

☐ 2 (Slightly accurate)　☐ 1 (Not at all)

2.3 The design size control using HoloDesigner:

☐ 5 (Extremely accurate)　☐ 4 (Very accurate)　☐ 3 (Moderately accurate)

☐ 2 (Slightly accurate)　☐ 1 (Not at all)

3 On-site design convenience using HoloDesigner

3.1 The comfort of HoloDesigner:

☐ 5 (Extremely comfortable)　☐ 4 (Very comfortable)　☐ 3 (Moderately comfortable)

☐ 2 (Slightly comfortable)　☐ 1 (Not at all)

3.2 The difficulty of learning HoloDesigner:

☐ 5 (Extremely easy)　☐ 4 (Very easy)　☐ 3 (Moderately easy)

☐ 2 (Slightly easy)　☐ 1 (Not at all)

3.3 The control of HoloDesigner:

☐ 5 (Excellent)　☐ 4 (Very good)　☐ 3 (Good)　☐ 2 (Fair)　☐ 1 (Poor)

Fig. 3.8. The questionnaire with the main questions.

Finally, we presented the results in means and standard deviation. We used The Kruskal–Wallis test to check the questionnaire answering tendency based on the "design experience" and "MR usage experience" of the participants. Regarding the statistical analysis process, we used the software SPSS® Statistics Base 22.

3.3 Results and analysis

In this section, we display and analyze the primary results of this design experiment on the basis of our research objective.

3.3.1 On-site design intuitiveness using HoloDesigner

In line with the interview, we could see that the mean and standard deviation of the score for the on-site design intuitiveness using HoloDesigner were 4.15 and 0.21 apart, as shown in Fig. 3.9, which primarily contained three specific elements.
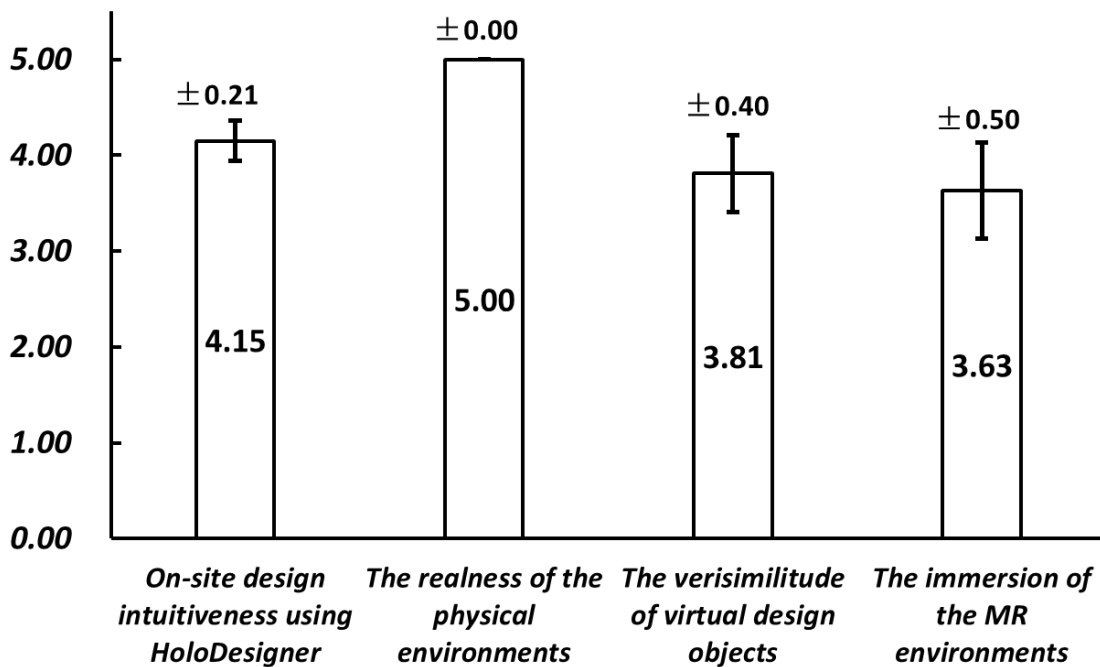
Fig. 3.9. The mean and standard deviation of the score for on-site design intuitiveness using HoloDesigner: real-ness of the physical environments, verisimilitude of the virtual design objects, and immersion of the MR environments.

First, in terms of the realness of the physical environments, the mean and standard deviation were 5.00 and 0.00, respectively (Fig. 3.9). All the participants nearly expressed that HoloDesigner never changed any details of the physical environment, and they could perceive the total real spatial relationship. Second, about the verisimilitude of the virtual design objects, as Fig. 3.9 shows, the mean and standard deviation were 3.81 and 0.40 apart. Most respondents expressed HoloDesigner

presented 3D shapes, precise scales, and vivid details for virtual objects. The small number of participants pointed out the 3D visualization of HoloDesigner sometimes had some chromatic aberration and sawtooth. Third, in respect to the MR environments' immersion, the mean and standard deviation were 3.63 and 0.50 separately (Fig. 3.9). Further, most respondents presented that the MR environments allowed them to move freely at the design site to understand the environmental details deeply and determine the appropriate design parameters through gesture and gaze interaction. However, several respondents said the hardware was heavy, and the field of visualization (FOV) was narrow, affecting their immersion experience.

Table 3.3. The Kruskal–Wallis test for different MR usage experience groups in on-site design intuitiveness using HoloDesigner.

	Mean ranks of Scores for the MR usage experience groups		P-value
	With MR usage experience	Without MR usage experience	（Kruskal-Wallis）
On-site design intuitiveness using HoloDesigner	11.00	7.36	0.112

Table 3.4. The Kruskal–Wallis test for different design experience groups in on-site design intuitiveness using HoloDesigner.

	Mean ranks of scores for the MR design experience groups			P-value
	1-10 Years	11-20 Years	21-30 Years	（Kruskal-Wallis）
On-site design intuitiveness using HoloDesigner	9.17	9.50	3.00	0.145

The Kruskal–Wallis test (Table 3.3, Table 3.4) displayed no noticeable differences in the average scores of on-site design intuitiveness using HoloDesigner in the different MR usage experience groups ($p=0.112>0.05$) or the various design experience groups ($p=0.145>0.05$). It suggested that improvements in on-site design intuitiveness derived from the technical features of HoloDesigner, regardless of user.

3.3.2 On-site design accuracy using HoloDesigner

According to the interviews, we could see that the mean and standard deviation of the score for on-site design accuracy using HoloDesigner were 3.65 and 0.56, respectively, which mainly contained three specific factors (Fig. 3.10).
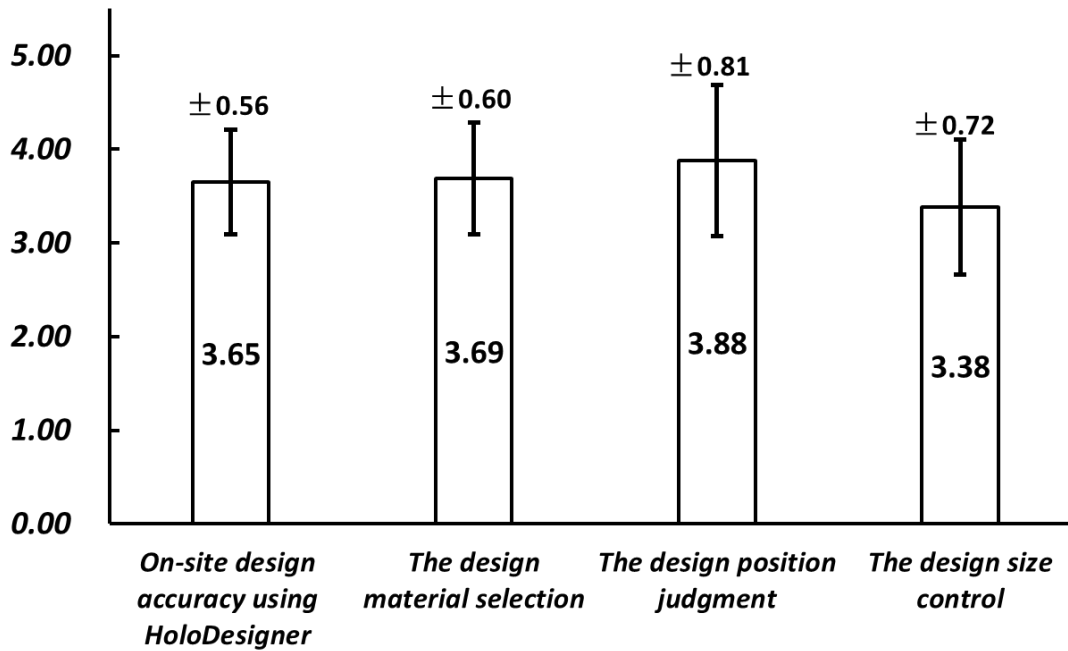
Fig. 3.10. The mean and standard deviation of the score for on-site design accuracy using HoloDesigner: design material selection, design position judgment, and design size control.

First of all, the mean and standard deviation for the design material selection were 3.69 and 0.60, respectively, as shown in Fig. 3.10. Most respondents expressed HoloDesigner was able to display lifelike colors and textures for the alternative design materials, which could help them make the relatively accurate materials judgment under the complex community scene. Next, as shown in Fig. 3.10, the mean and standard deviation were 3.88 and 0.81, respectively, regarding the design position judgment. The participants generally responded HoloDesigner reflected the authentic spatial relationship, which contributed to them making the relatively precise position judgment. At the same time, using the measurement function of HoloDesigner, they could get the accurate spatial distance and coordinates. However, a few respondents with rich design experience did not think so. They expressed they could still make accurate spatial

position judgments using their visual imagination without HoloDesigner. Then, about the design size control, the mean and standard deviation were 3.38 and 0.72 separately (Fig. 3.10). Similar to the design position judgment, most respondents said HoloDesigner could assist them in making the effective design size control. Nevertheless, the ones having rich experience expressed that HoloDesigner was mediocre for accurate design size control. Further, a few participants stated that they were unfamiliar with the controlling method and had difficulties controlling the precise size.

Table 3.5. The Kruskal–Wallis test for different MR usage experience groups in on-site design accuracy using HoloDesigner.

	Mean ranks of scores for the MR usage experience groups		P-value
	With MR usage experience	Without MR usage experience	（Kruskal-Wallis）
On-site design accuracy using HoloDesigner	11.90	6.95	0.049

Table 3.6. The Kruskal–Wallis test for different design experience groups in on-site design accuracy using HoloDesigner.

	Mean ranks of scores for the design experience groups			P-value
	1-10 Years	11-20 Years	21-30 Years	（Kruskal-Wallis）
On-site design accuracy using HoloDesigner	10.56	7.50	1.75	0.036

Through the Kruskal–Wallis test (Table 3.5), we could find noticeable differences (p=0.049<0.05) in the average scores for on-site design accuracy using HoloDesigner between different MR usage experience groups. To be specific, participants with MR usage experience were more familiar with control skills of related MR devices and made a notably higher score for on-site design accuracy, as shown in Fig. 3.11. The Kruskal–Wallis test (Table 3.6) also revealed obvious differences (p=0.036<0.05) in average ratings of on-site design accuracy using HoloDesigner among different design experience groups. Further, we could see a clear downward trend for average ratings

with increasing design experience from Fig. 3.12.
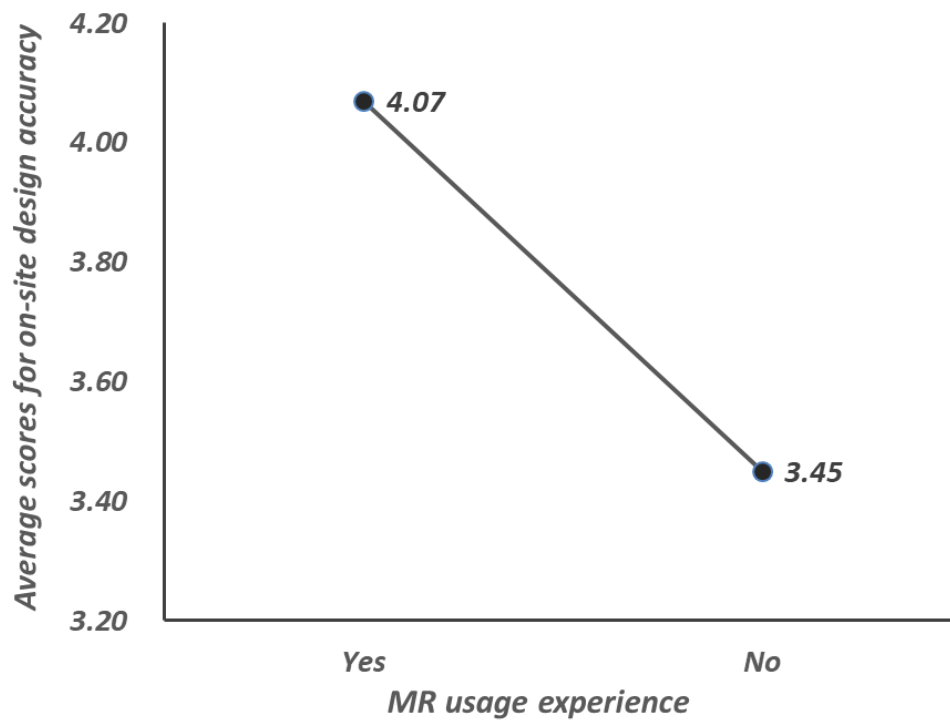
Fig. 3.11. The average scores for on-site design accuracy using HoloDesigner in different MR usage experience groups.
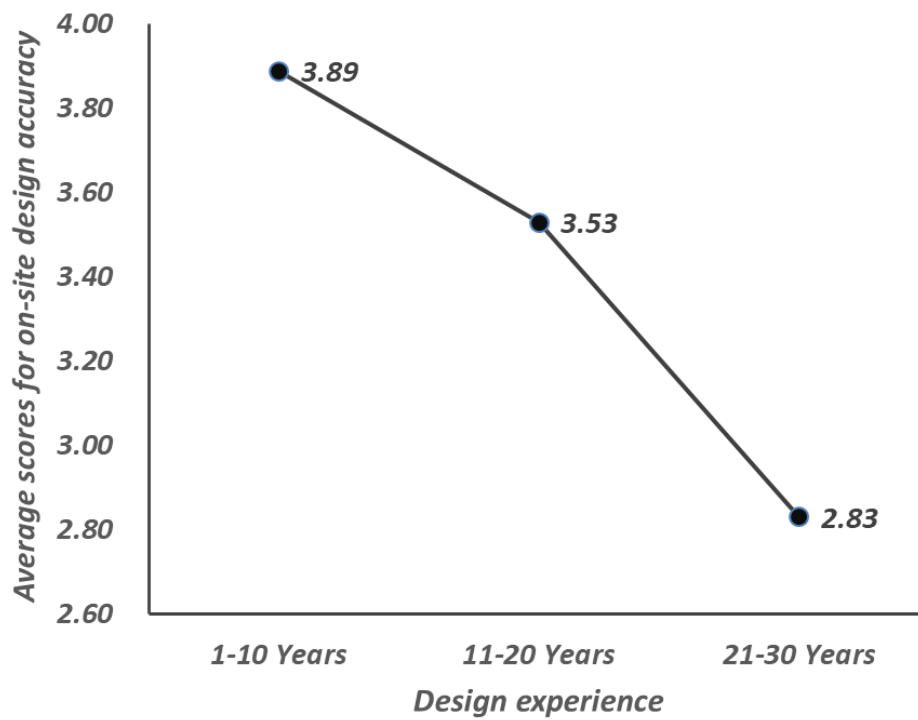
Fig. 3.12. The average scores for on-site design accuracy using HoloDesigner in different design experience groups.

3.3.3 On-site design convenience using HoloDesigner

According to the interview, as shown in Fig. 3.13, the mean and standard deviation for on-site design convenience using HoloDesigner were 3.90 and 0.36 separately, mainly referring to three critical factors.
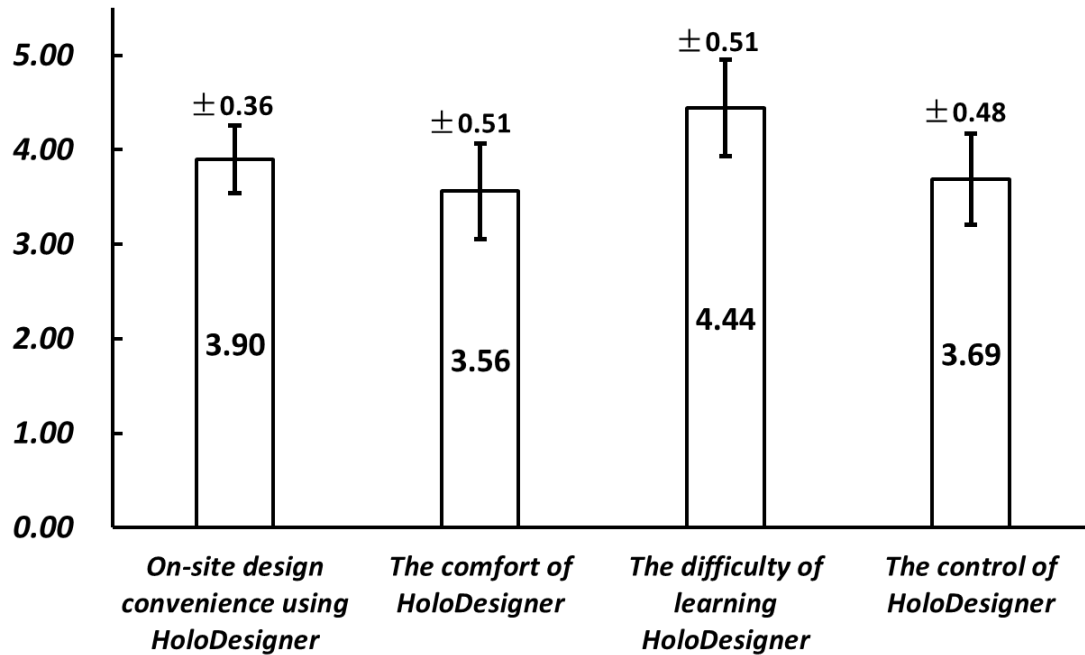
Fig. 3.13. The mean and standard deviation of the score for the on-site design convenience using HoloDesigner: comfort of HoloDesigner, difficulty of learning HoloDesigner, and control of HoloDesigner.

First, about the comfort of HoloDesigner, the mean and standard deviation were 3.56 and 0.51 apart (Fig. 3.13). In the experiment, we could see some participants used their hands to support the weight of Microsoft HoloLens. Nevertheless, most participants stated they did not feel uncomfortable in their design experience. Only a few respondents said that Microsoft HoloLens was unfriendly for someone wearing glasses. Second, as to the difficulty of learning HoloDesigner, the mean and standard deviation was 4.44 and 0.51 separately (Fig. 3.13). Most participants expressed they could master the basic usage skills of HoloDesigner through the brief usage guide. In addition, the experiment suggested nearly all the participants could make the basic

design actions using HoloDesigner. Third, respecting the control of HoloDesigner, the mean and standard deviation were 3.69and 0.48, respectively, as shown in Fig. 3.13. This experiment found that nearly all the participants could complete basic real-time design manipulation using HoloDesigner. However, the majority of them said that they were not familiar with gaze positioning and gesture controlling and spent an enormous effort doing some simple design manipulation.

Table 3.7. The Kruskal–Wallis test for different design experience groups in on-site design convenience using HoloDesigner.

	Mean ranks of scores for the design experience groups			P-value
	1-10 Years	11-20 Years	21-30 Years	（Kruskal-Wallis）
On-site design convenience using HoloDesigner	**11.22**	**6.20**	**2.00**	**0.014**

Table 3.8. The Kruskal–Wallis test for different MR usage experience groups in on-site design convenience using HoloDesigner.

	Mean ranks of scores for the MR usage experience groups		P-value
	With MR usage experience	Without MR usage experience	（Kruskal-Wallis）
On-site design convenience using HoloDesigner	**11.50**	**7.14**	**0.077**

From the Kruskal–Wallis test (Table 3.7), we could see noticeable differences (p=0.014<0.05) in the average score of on-site design convenience using HoloDesigner among different design experience groups. We found that the average rating dropped significantly with the increase of design experience (Fig. 3.14). However, there were no differences (p=0.077>0.05) identified between the different MR usage experience groups according to the Kruskal–Wallis test (Table 3.8). Most participants stated that the essential manipulation of HoloDesigner was easy to master, even those who had no MR experience before.
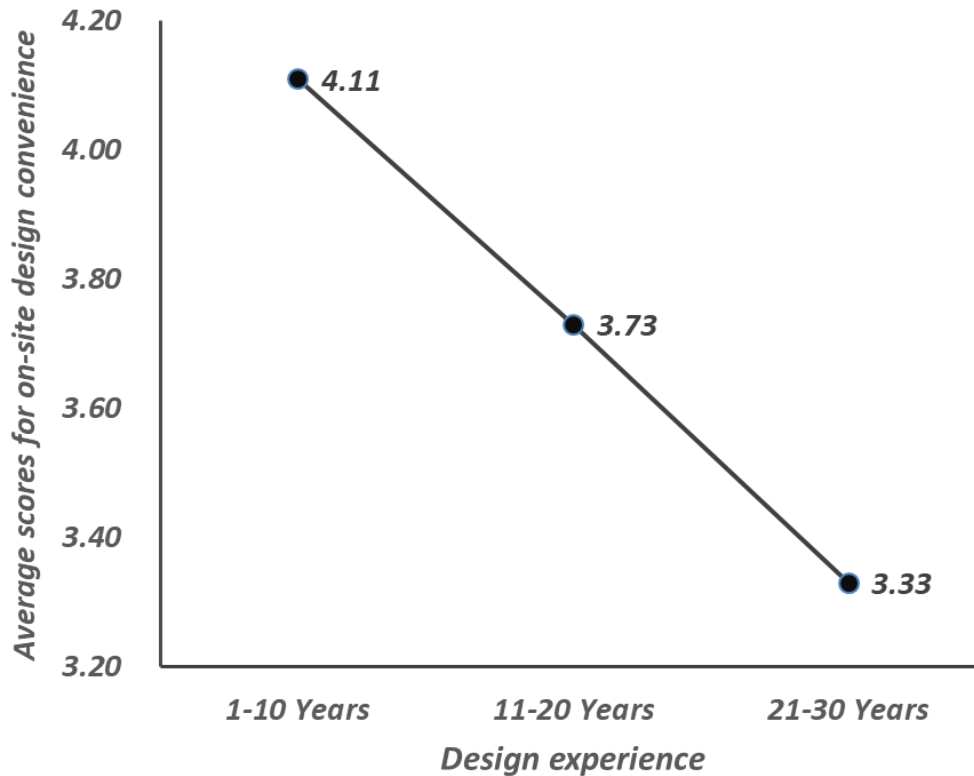
Fig. 3.14. The average scores for on-site design convenience using HoloDesigner in different design experience groups.

3.4 Discussion and conclusion

This research intended to apply Holodesigner to assist professionals in making design proposals on-site. We performed an on-site design experiment at a typical community environment improvement scene with sixteen participants to examine the effectiveness. The experimental results showed that HoloDesigner could provide professionals (especially those with weak design experience) with intuitive design perception, accurate design judgments, and convenient design adjustments, thus effectively assisting them in making design proposals on-site in the design concept stage.

To be more specific, HoloDesigner can make a mixed visualization environment where virtual 3D design objects would be displayed in the real world. Thus, in the MR environment, professionals can deeply perceive the complex environmental particulars

and make design concepts intuitive. In addition, the MR environment reflects the totally real spatial depth and relationship, which contributes to professionals making relatively precise positions and size judgments at the design site. Meanwhile, the lifelike texture provided by HoloDesigner can assist professionals in selecting the appropriate materials. Moreover, the usage of HoloDesigner is not complicated. Professionals can master the basic usage skills and conveniently make real-time design adjustments according to actual environmental details with a brief usage guide.

Significantly, we can find that despite all the participants approved the benefits of HoloDesigner for assisting them in making design proposals on-site, the experienced ones gave relatively low scores. In this regard, they have formed a set of mature design habits depending on visual imagination during many years of design practice. Despite experiencing the benefits of HoloDesigner in the design experiment, professionals still hardly change the long-standing design habits in a short time. The professionals with rich design experience universally expressed HoloDesigner could be a potential supplement for assisting on-site design works in community environment improvement.

Nevertheless, our research has several limitations. Firstly, about the hardware, we chose Microsoft HoloLens, which was the most advanced wearable device at that time. Its technological features (like the 3D visualization, the control methods based on gesture and gaze, and the spatial depth perception) matched our research purpose perfectly. Whereas, considering its weight (579g), Microsoft HoloLens is not suitable for wearing for long hours. Moreover, regarding the low endurance (less than three hours) of battery, Microsoft HoloLens hardly support sustainable outdoor design work. Moreover, its relatively narrow FOV hardly displays the whole MR scene, which might negatively influence professionals' perception and judgment. Second, concerning the software, as there was no suitable application software in the official Microsoft Store, we implemented HoloDesigner by our research team. Because we are not professional

software developers, the appearance, fluency, and stability of HoloDesigner need to be improved. Additionally, Holodesigner is just equipped with some essential functions that scarcely support the relatively complicated design deduction. Thirdly, the design data (3D models and 2D materials) used in the experiment was prepared in advance, which might limit participants' on-site design imagination. The present data preparation process is very complex, which contains data creation, data edition, data uploading, and data loading coding. Fourthly, respecting participants, some of them are from the same design institute. Therefore they might form an apriori attitude towards the new technology in daily work, which might affect their performance in the experiment. Besides, the relatively small sample size might not reflect the perspective of all professionals. Fifthly, because of the simple experimental tasks and limited hardware performance, the design experience time for the single participant was just ten minutes. It might be difficult for participants to make total sense of HoloDesigner and make a reasonable judgment.

In the future, we intend to improve the HoloDesigner and apply it in the design deliberation stage to support citizens' design understanding and demands expression, thus narrowing the semantic differences between the professionals and citizens.

Chapter 4. Applying HoloDesigner to narrowing design semantic differences between citizens and professionals

4.1 Introduction

4.1.1 Research background

In recent years, community public space has begun to play a more important role, carrying on the more prosperous daily life of citizens (Houa & Grohmannb 2018). Thus, citizens have gradually been encouraged to participate in the design deliberation process of their community public space. However, the semantic differences between citizens and professionals always resulted in some misunderstandings. On the one hand, citizens hardly understand professional design documents accurately. On the other hand, citizens also scarcely express their design demands clearly.

4.1.2 Related works

The technical leap of computer graphics brings the potential to bridge the gap between citizens and professionals in community environment improvement. In particular, Mixed Reality (MR), a new computer graphic technology, could merge virtual objects into the real world (Milgram & Kishino, 1994).

From the 1990s, researchers began to apply MR to facilitate communication and narrow semantic differences between citizens and scholars in the design deliberation process. Feiner et al. (1995) used MR technology to create an "X-ray vision" for users to view the alternative virtual design elements overlaying on the actual building place.

Subsequently, the participatory design table-top based on MR technology became the primary method to facilitate design communication between citizens and professionals. Typically, URP and Luminous Table offered an MR interactive space for design proposal discussion. They also provided citizens with simple sketches inputting (Underkoffler & Ishii, 1999; Ishii et al., 2002). However, they used physical models

that could not be adjusted in real-time. Meanwhile, the sketches inputting was rough. Therefore, citizens could not express their design demands clearly. The subsequent works began used virtual models and upgraded the design inputting methods. The famous design table-top ARTHUR firstly created wand and gesture interaction for the citizens viewing and editing virtual design objects from the first-person view (Broll et al., 2004; Schieck et al., 2005; Wang, 2013). However, the design deliberation based on these MR design table-tops always was limited at the laboratory, never immersing into the real environment.

Therefore, MR technology began to be used to support participatory design in the real design scene. Typically, MR Tent, an on-site physical enclosing system, brought the laboratory technologies to design sites and provided the citizens with an interactive approach to understand the professional design concept and convey their design demands (Sareika & Schmalstieg, 2007; Maquil et al., 2009). However, MR Tent involved a number of devices and complicated on-site installations (Sareika, 2010). Besides, citizens and professionals could only make design discussions from some limited design viewpoint because of the fixed webcam.

Subsequently, researchers began to develop MR design support systems based on the mobile device (especially for smartphones) for supporting participatory design (Oksman et al., 2014). The early MR design support system on smartphones mainly focused on providing the citizens with on-site visualization for understanding the abstract design concept and alternative design elements (Allen et al., 2011). Then, some interactive functions had been developed, which could offer real-time manipulation for citizens to adjust the position, appearance, shape, and size of virtual design objects on-site, thus expressing their design demands (Skov et al., 2013). However, the 2D screen display based on the smartphone can hardly provide the citizens with an intuitive visual understanding (Wang, Chen, & Chen, 2018). Similarly, the narrow tangible interaction

interface based on the smartphone can barely support citizens to make effective design demands expression (Chi et al., 2013).

With recent technology improvements, more advanced wearable MR devices have emerged. In particular, Microsoft HoloLens (Microsoft, Redmond, WA) is equipped the unique features like 3D visual display, special interaction mode, and spatial depth perception. Based on Microsoft HoloLens, we have successfully implemented an MR design support system for participatory design (See Chapter 2), which provides the possibilities to facilitate narrow semantic differences between citizens and professionals.

4.1.3 Research objective

Therefore, this research intends to apply HoloDesigner to narrow the semantic differences between citizens and professionals in community environment improvement. Further, this research plans to use HoloDesigner to assist citizens in understanding the professional design proposal and expressing their design demands in the design deliberation stage. Thus, a design experiment for a specific campus community public space was performed with twelve participants to examine the effectiveness.

4.2. Methods

4.2.1 MR design support system-HoloDesigner
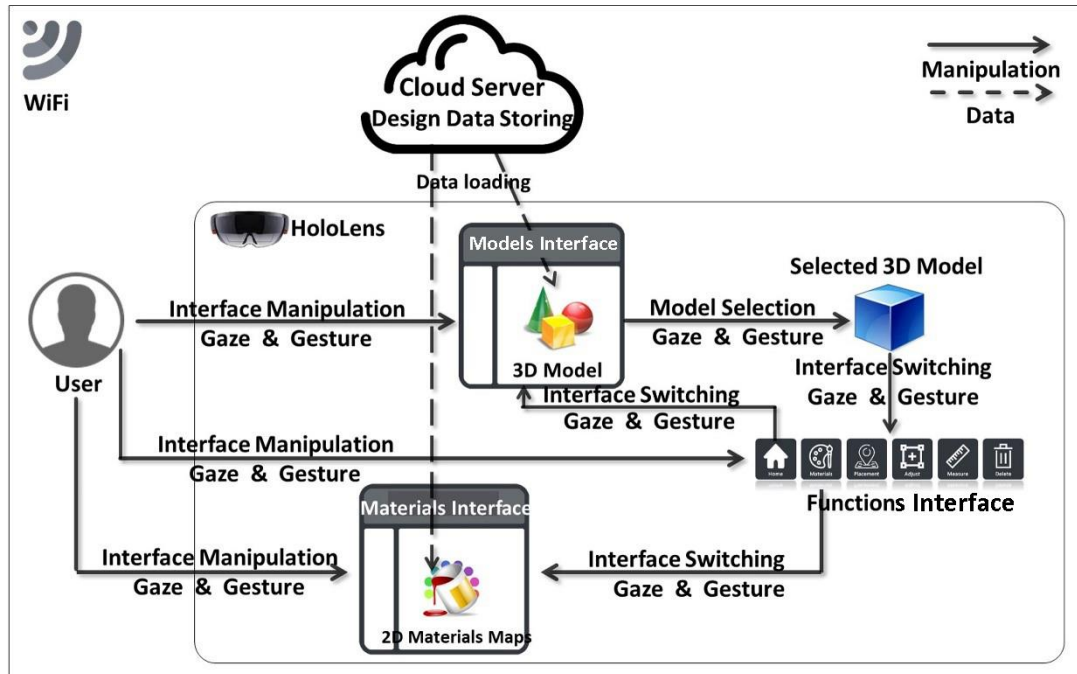
Fig. 4.1. Concept of HoloDesigner.

HoloDesigner is an MR design support system on Microsoft HoloLens for participatory design. HoloDesigner was developed by our research team using the Unity 3D engine in C sharp language (the development details are in chapter 2), which mainly realize on-site 3D visualization and real-time interaction of design objects in the WiFi environment. As Fig.4.1 shows, HoloDesigner has three interactive interfaces. In this regard, the three interfaces contain the models interface for loading 3D models, the materials interface for loading 2D materials pictures, the functions interface for offering several essential design functions. These design functions include model adjustment (moving, rotating, scaling), model placement, model materials selection, model deletion, and distance measurement. Design data (containing 3D models and 2D materials) are loaded from a cloud server. In addition, the particular interaction depending on gaze and gesture from Microsoft HoloLens is ready to be introduced for

users' control. Meanwhile, the creative physical contact between the virtual objects and the real environment also is planned to be realized through the unique spatial mapping of Microsoft HoloLens.

4.2.2 Design experiment

To validate the feasibility of HoloDesigner for narrowing semantic differences between citizens and professionals in the deliberation stage, we performed a design experiment with twelve participants at a typical campus community public space.

4.2.2.1 Experimental scene
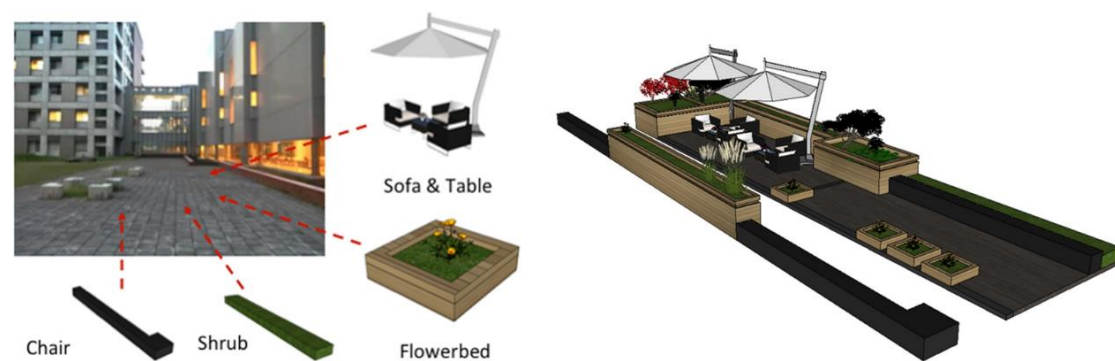
Fig. 4.2. Experimental scene and preliminary design proposal.

We selected a typical design scene of campus community public space as the experimental case in the research. This community public space is located at Kanazawa University, Kakuma Machi of Kanazawa City in Japan, which was preliminarily planned to add some greens and street furniture according to the citizens' demands and professionals' suggestion (Fig. 4.2).

4.2.2.2 Data preparation
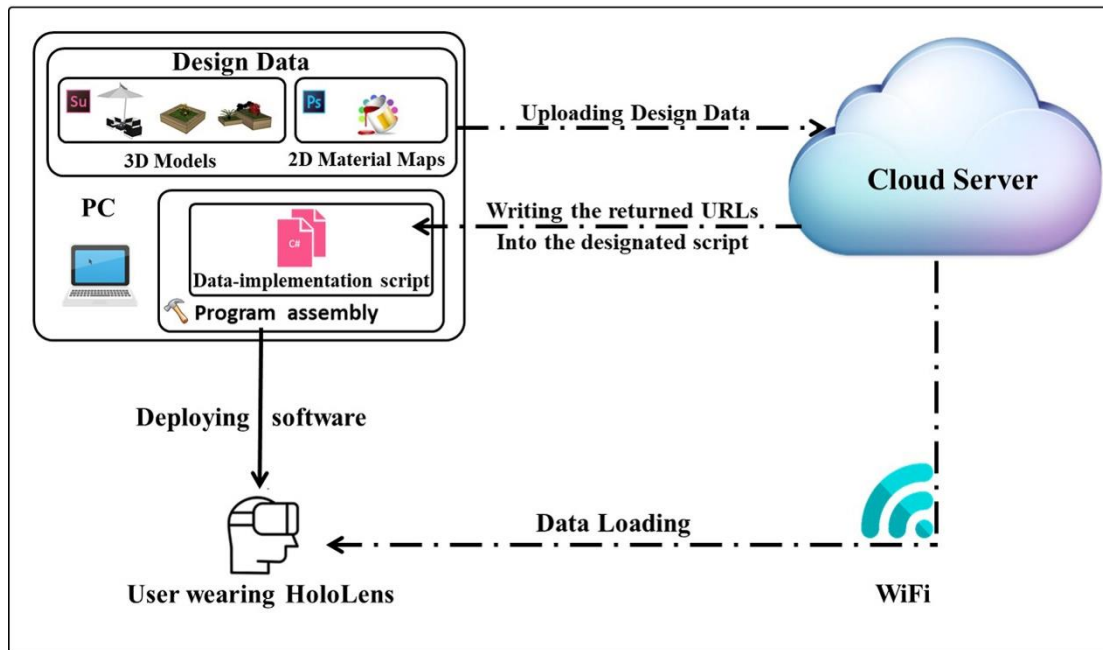
Fig. 4.3. Data workflow.

Therefore, according to the design proposal, we created corresponding 3D models using Google SketchUp and 2D material maps using Adobe Photoshop for the planned greens and street furniture and uploaded them into the designated cloud server (Qiniuyun) to get the corresponding Uniform Resource Locators (URLs). Finally, we wrote these URLs in the designated data implementing script of the program assembly of HoloDesigner, thus completing the data preparation (Fig. 4.3).

4.2.2.3 Participants

The twelve participants included six women and six men. All of them were lay people from the local campus community. Their familiarity with participatory design and MR technology was collected through the following questionnaire survey.

4.2.2.4 Experimental procedures
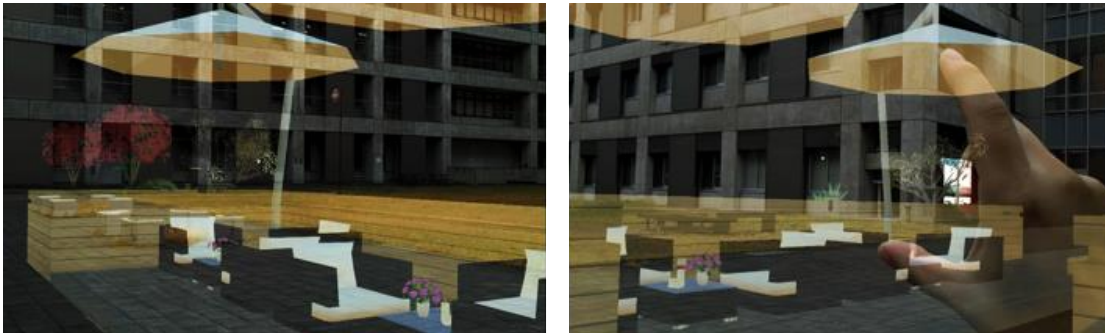
Fig. 4.4. The experimental process scene through HoloDesigner.

After a brief usage guide (about five minutes) for HoloDesigner, each participant began his or her participatory design experience (Fig. 4.4). Specifically, each participant firstly viewed the professional design proposal under the real design scene using HoloDesigner. Each participant then expressed his or her design demands or intentions through make real-time design adjustments using HoloDesigner.

Subsequently, we made a questionnaire survey with each participant to validate the feasibility of HoloDesigner for narrowing semantic differences between citizens and professionals. The following questions were asked, all ranked on a five-point Likert scale:

Q1. Are you familiar with participatory design?

(1: Not at all, 2: Slightly, 3: Moderately, 4: Very, 5: Extremely)

Q2. Are you familiar with MR technology?

(1: Not at all, 2: Slightly, 3: Moderately, 4: Very, 5: Extremely)

Q3.Does HoloDesginer make the professional design proposal understandable?

(1: Not at all, 2: Slightly, 3: Moderately, 4: Very, 5: Extremely)

Q4.Is HoloDesginer helpful to express your design demands?

(1: Not at all, 2: Slightly, 3: Moderately, 4: Very, 5: Extremely)

Finally, we described the questionnaire survey results in means and standard deviation. In addition, we used the correlation analysis to further explain the results

according to the participants' familiarity with community design and MR technology.

4.3. Results and analysis

4.3.1 Descriptive statistics
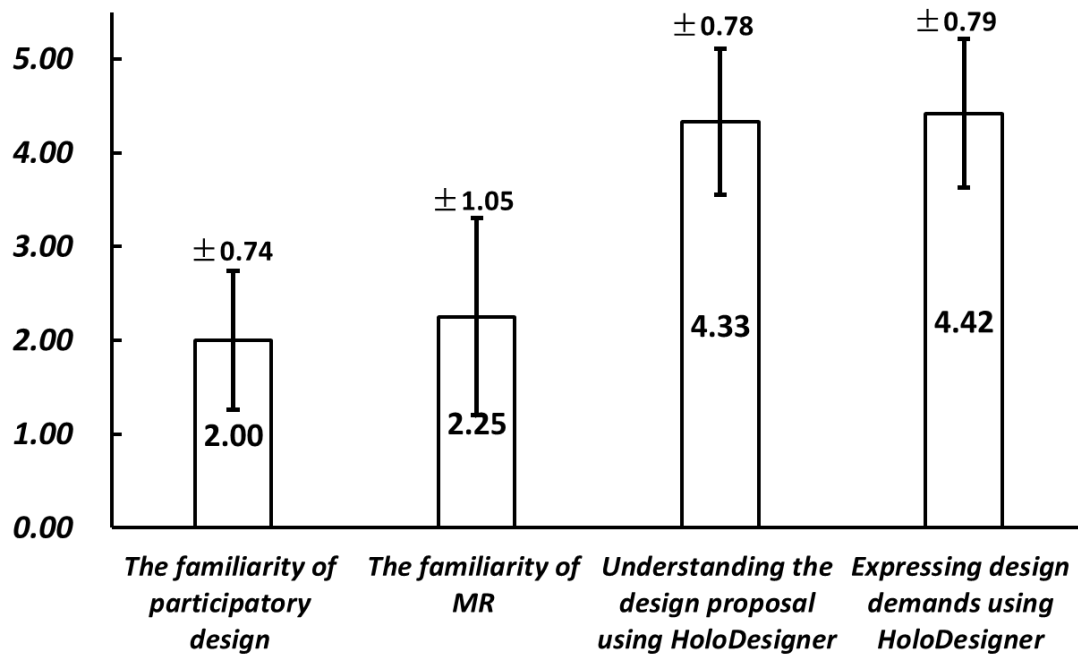
Fig. 4.5 The mean and standard deviation of the scores for the main questions of the questionnaire survey.

Fig. 4.5 presents the scores (mean and standard deviation) for the primary questions of the questionnaire survey. In this regard, in terms of the familiarity of participatory design, most participants gave relatively low ratings (mean ± standard deviation: 2.00±0.74) because they hardly took part in the corresponding design works. About the familiarity of MR technology, most respondents made relatively negative evaluations (mean ± standard deviation: 2.25±1.05) because they learned little about this advanced technology. Meanwhile, Fig. 4.5 displays the relatively high scores (mean ± standard deviation: 4.33±0.78 and 4.42±0.79) for participants understanding the professional design proposal and expressing design demands using HoloDesigner apart. The results demonstrated the potential positive effects for HoloDesigner narrowing the

semantic differences between citizens and professionals in the design deliberation process.

4.3.2 Correlation analysis

Table 4.1. The skewness of the scores for the main questions of questionnaire survey.

		The familiarity with participatory design	The familiarity with MR	Understanding the professional design proposal using HoloDesigner	Expressing design demands using HoloDesigner
Skewness	Statistic	-0.000	0.522	-0.719	-0.988
	Std. Error	0.637	0.637	0.637	0.637

As most scores for the main questions of the questionnaire survey were in skewed distribution (Table 4.1), we used Spearman's rank correlation coefficient to examine their correlation.

Table 4.2. Spearman's rank correlation coefficient between the scores for participatory design experience using HoloDesigner and the familiarity of participants with participatory design and MR technology.

		Understanding the professional design proposal using HoloDesigner	Expressing design demands using HoloDesigner
The familiarity with participatory design	Correlation Coefficient	0.791	0.000
	P-value	0.002	1.000
The familiarity with MR	Correlation Coefficient	-0.111	0.733
	P-value	0.12	0.007

We can see a strong positive correlation (correlation coefficient and P-value: 0.791 and 0.002) between the familiarity of participatory design and understanding the professional design proposal using HoloDesigner (Table 4.2). Similarly, Table 4.2 suggested a strong positive correlation (correlation coefficient and P-value: 0.733 and 0.007) between the familiarity of MR technology and expressing design demands using

HoloDesigner.

Nevertheless, we could not find a significant correlation (correlation coefficient and P-value: -0.111 and 0.012) between the familiarity of MR technology and understanding the professional design proposal using HoloDesigner. (Table 4.2). In addition, there was no identified correlation (correlation coefficient and P-value: 0.000 and 1) between the familiarity of participatory design and expressing design demands using HoloDesigner (Table 4.2).

4.4 Discussion

4.4.1 Understanding the professional design proposal using HoloDesigner
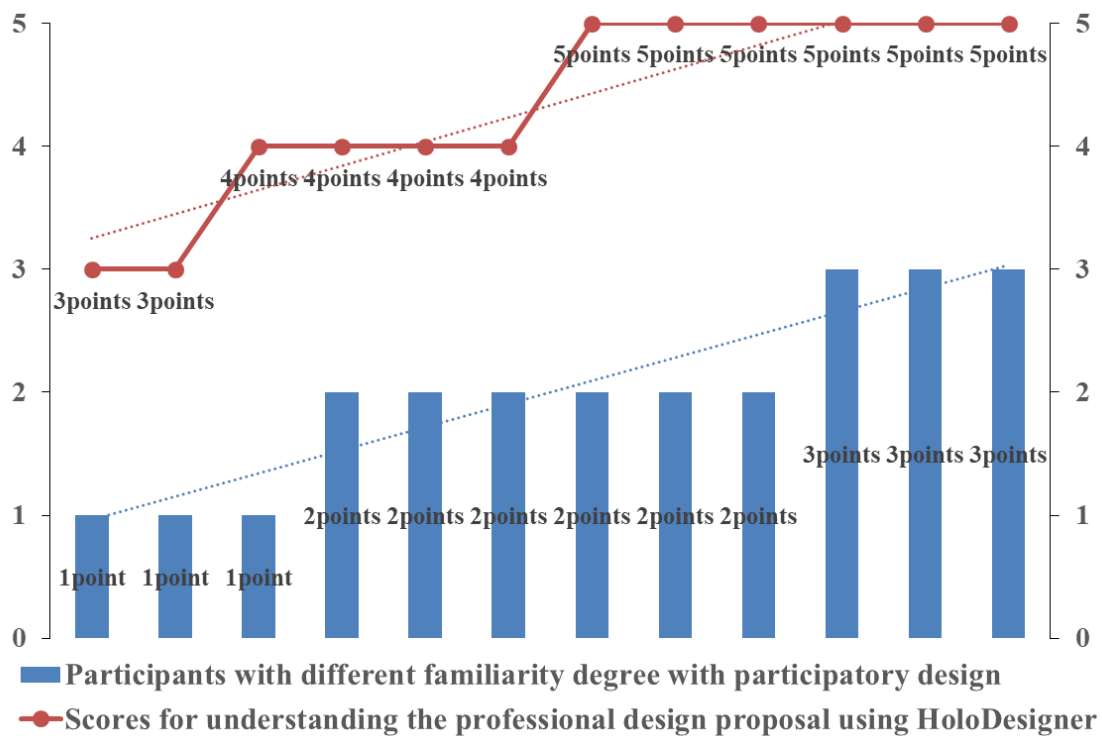
Fig. 4.6. The scores distribution for understanding the professional design proposal using HoloDesigner based on the familiarity with participatory design of participants.

From Fig. 4.6, we could find most of the participants believed HoloDesigner could make the professional design proposal more understandable. Six participants gave five points, and four participants rated four points. Nevertheless, two respondents with low

65

familiarity with participatory design only gave three points. Furthermore, there was an apparent increasing trend for the scores of understanding the professional design proposal with the increased familiarity degree with participatory design, which further explains the correlation analysis results (Fig. 4.6).

In this regard, HoloDesigner could immerse the virtual design objects in the real campus community environment for on-site visualization. Furthermore, this visualization rendered the 3D form and exact scale for the virtual design objects. In addition, this visualization described a totally real spatial relationship. Moreover, this visualization was able to allow participants to move freely at the design site to select the appropriate viewing angle to understand the vivid design proposal intuitively instead of tenebrous design documents. Whereas, a small number of participants who never participated in the corresponding participatory design works could not recognize the significant benefits from HoloDesigner.

4.4.2 Expressing design demands using HoloDesigner
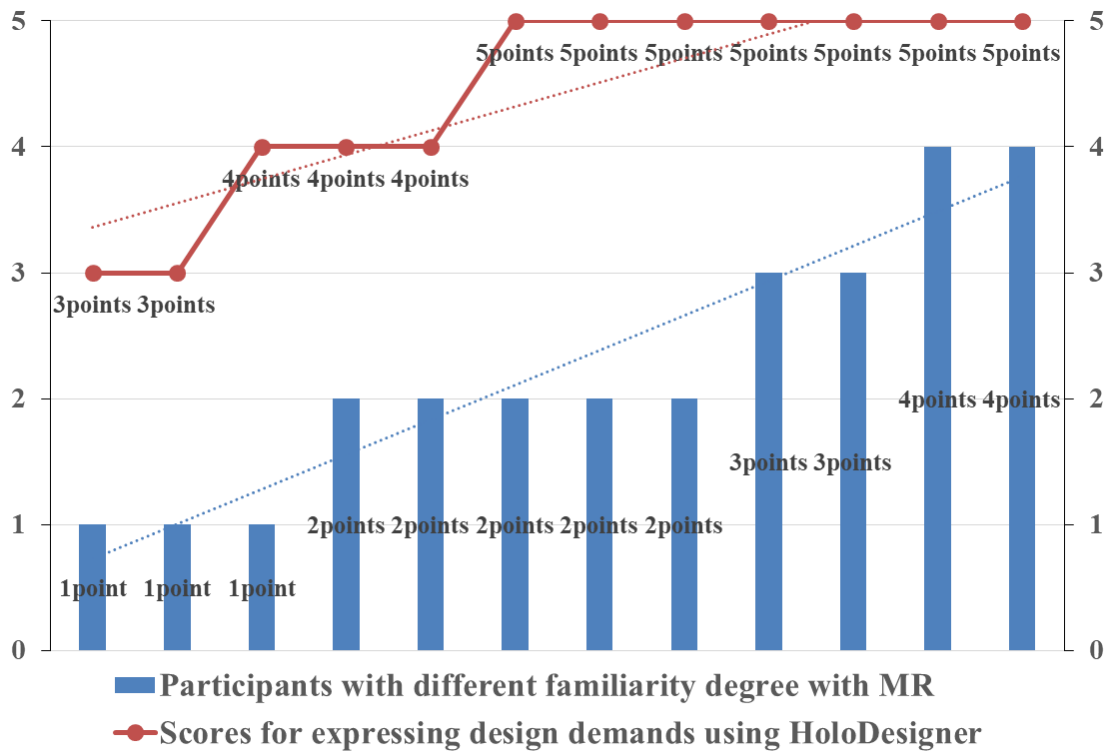
Fig. 4.7. The scores distribution for expressing design demands using HoloDesigner based on the familiarity with MR technology of participants.

According to Fig. 4.7, we found most participants believed HoloDesigner was helpful for expressing their demands. Seven respondents rated five points, and three respondents scored four points. However, two respondents with a low familiarity degree with MR technology just scored three points. In addition, we could see the ratings for expressing design demands using HoloDesigner rose significantly as the increase of familiarity degree with MR technology, which also validated the correlation analysis results further (Fig. 4.7).

Specifically, HoloDesigner created a convenient approach for participants expressing design demands. First, the design data in HoloDesigner were prepared beforehand in line with the preliminary design proposal, which contributed to the participants making quick design judgments instead of complicated and tedious design deductions in conventional design methods. Moreover, the usage of HoloDesigner was

relatively easy. By a brief usage instruction, most of the participants could select the suitable design objects and set the appropriate design parameters through gaze positioning and gesture controlling. However, only a few respondents with a low familiarity degree with MR technology could not master the essential control skills of HoloDesigner in a short time, thus not expressing design demands smoothly.

4.4.3 Limitations

However, this research still has some limitations. First, the narrow field of view (FOV) made it hard for the participants to view the design proposal in the whole MR scene. Second, there are some chromatic aberrations and sawtooth for sometimes rendering virtual design objects under strong sunlight. These two limitations might affect the participants' understanding of the professional design proposal. Third, HoloDesigner operated slowly with laggy manipulation when meeting with the relatively complex design objects. Fourth, design data used in the experiment were prepared in advance, which might limit the imagination of the participants. The latter two limitations might affect the participants to express their design demands.

4.5 Conclusion

In this research, we applied HoloDesigner to narrow the semantic differences between citizens and professionals in community environment improvement. Through a design experiment with twelve participants, we have demonstrated HoloDesigner can assist citizens in understanding the professional design proposal and expressing their design demands, thus facilitating the design deliberation process of participatory design.

Concretely speaking, HoloDesigner could realize intuitive on-site 3D visualization of design objects. It could assist citizens in experiencing and understanding the spatial relationship, scale, and details of the professional design proposal in the real community scene intuitively, avoiding abstract and complex design imagination relying on conventional design documents.

Meanwhile, HoloDesigner could achieve real-time design manipulation. It provided a convenient approach for the citizens to adjust the design objects directly by gesture and gaze, instead of conveying design demands using indirect language, drawing, or texts.

In the future, we intend to improve HoloDesiner for more clear display, more stable operation.   More importantly, we plan to expand it to a multi-users sharing scene for supporting participatory design.

Chapter 5. Conclusions

5.1 Main findings

In this thesis, an MR design support system, HoloDesigner, was developed to support participatory design. Two empirical design experiments were performed to examine the effectiveness of HoloDesigner to assist citizens and professionals in different design stages. Furthermore, this thesis expands on understanding the role that the new technology such as MR could play in the design perception, deduction, expression, and communication in the participatory process. From a theoretical view, this thesis attempts to integrate computer fields into design fields, applying computer graphics to participatory community design. From a practical perspective, insights from this research will be a valuable resource for developing and applying a new technical tool to actual planning and design projects for participatory design. In summary, we can draw the following conclusions from this research.

5.1.1 HoloDesigner can realize on-site 3D visualization and real-time manipulation for 3D design models

Since the 1960s, Participatory design has been consistently encouraged in community planning and design. However, limited by the technical tools, 3D design models were difficult to merge into the actual community environment for on-site visualization and real-time interaction. It affected the design perception and deduction of professionals and citizens and influenced their design communication.

In this research, to address the limitations, we use MR technology to design and develop a design support system called HoloDesigner. Unity 3D game engine was employed as the core development platform. Through the three essential steps, creating assets, developing MR application software, and deploying MR application software, HoloDesigner was implemented successfully. We then demonstrated its main workflow

and functionalities. The results proved that HoloDesigner could successfully render on-site 3D visualization of virtual objects, which offered the immersive experience possibilities for users to perceive the environmental details and understand the design concept. At the same time, the results also suggested HoloDesigner realized real-time manipulation of 3D models, which provided users with a convenient approach to deduct their design concept and express design demands.

5.1.2 HoloDesigner can assist professionals in making design proposals on-site in the concept stage of participatory design

We recruited sixteen participants (professionals) to participate in an on-site design experiment at a typical community environmental improvement scene. In this experiment, participants were required to perceive the community environments, make preliminary design deductions, and design adjustments on-site using HoloDesigner. Interviews and questionnaires were used to evaluate its effectiveness. The experimental results showed that HoloDesigner could provide participants (especially those with weak design experience) with intuitive design perception, accurate design judgments, and convenient design adjustments, thus effectively assisting them in making design proposals on-site in the design concept stage.

5.1.3 HoloDesigner can narrow design semantic differences between citizens and professionals in the deliberation stage of participatory design

Subsequently, to examine the feasibility of HoloDesigner for narrowing the semantic differences between citizens and professionals in the design deliberation stage of participatory design in community environment improvement.

We invited twelve participants (lay people from the local community) to participate in a design experiment for a specific campus community public space. In this experiment, participants were first required to use HoloDesigner to visualize the professional design proposal and then make real-time design adjustments using

HoloDesigner to express their design demands. Interviews and questionnaires were also used to examine the feasibility. The results suggested the most participants could understand the professional design proposal accurately through the intuitive 3D visualization of HoloDesigner. Meanwhile, most respondents could express clearly their design demands by adjusting the design proposal in real-time using HoloDesigner. This work proved HoloDesigner could narrow the semantic differences between citizens and professionals, thus facilitating participatory design.

5.2 Limitations

5.2.1 The shortages of HoloDesigner

This MR design support system HoloDesigner is based on Microsoft HoloLens, whose technical characteristics match our research purpose perfectly. However, its heavyweight and low battery could not support users make design activities over long periods. Also, the narrow FOV of the Microsoft HoloLens cannot present the whole MR environment, affecting environmental perception and design judgment to some extent. At the same time, the software was developed by us in-house. As we are not professional programmers, the current appearance, fluency, and stability of HoloDesigner need to be improved. Besides, HoloDesigner is only equipped with some essential design functions, which hardly support relatively complicated design works.

5.2.1 The limitations of the experiments

This research has proved that this MR design support system HoloDesigner can assist professionals and citizens in the concept and deliberation stages of participatory design through two empirical design experiments. However, there are some limited experimental conditions, such as the relatively small sample size, the relatively short experimental time, and the relatively simple experimental tasks.

5.3 Future works

In the future, we will continue to work on optimizing HoloDesigner for a smoother operation, easier data preparation, friendlier control, and more prosperous functions. We hope to apply it to facilitate the participatory design process in actual community planning and design projects.

Publications

1. **<u>Yuze Dan</u>**, Zhenjiang Shen, Jianqiang Xiao, Yiyun Zhu, Ling Huang, Jun Zhou. HoloDesigner: A Mixed Reality Tool for On-Site Design. *Automation in Construction*, 129, 103808, 2021. (SCI, IF=7.7)

2. **<u>Yuze Dan</u>**, Zhenjiang Shen, Yiyun Zhu, Ling Huang. Using Mixed Reality (MR) to Improve On-Site Design Experience in Community Planning. *Applied Sciences*, 11(7), 3071, 2021. (SCI, IF=2.679)

3. **<u>Yuze Dan</u>**, Zhenjiang Shen, Yumin Lin, Yiyun Zhu, Jianqiang Xiao. The development of design support system for public participation of community public space design using Mixed Reality. *Proceedings o*f *the 39th eCAADe Conference (Novi Sad, Serbia)*, Vol. 1, pp.205-212, September, 2021.

4. Ling Huang, **<u>Yuze Dan</u>**, Jianfeng Xu, Miao Tong. From Concept to Action: Practice and Thinking in Urban Community Development and Community Planning in Chongqing. *International Review for Spatial Planning and Sustainable Development*, Vol.6, No.2, pp. 1-11, 2018.

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