Integrating XR and Tangible Model to Enhance Old Building Renovation Design

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The renovation of old buildings usually has complex site constraints, involves multiple interests, and has limited capital costs. Therefore, the transformation process has always encouraged the participation of stakeholders to improve the effectiveness of the design. Tangible user interfaces (TUIs) consisting of physical models further simplify the operation. However, most designs are displayed by projection, which cannot provide a realistic interactive experience. Extended Reality (XR) technology has the advantages of interactivity and clear visualization. We developed a participatory renovation tool using XR technology and tangible models. We invited the owner to view the 3D design proposal in HoloLens and then use the tangible model to discuss the renovation design. This experiment proves that the system can realize on-site 3D visualization, allowing the public to design in a real environment and intuitively interact with the virtual and the real. Using the participatory design method of XR technology + tangible model will provide a convenient platform for the renovation of old buildings with the collaborative participation of stakeholders.

Keywords: *Building Renovation Design, Participatory Design, Extended Reality, Tangible Model, HoloLens*

INTRODUCTION

Modern society is moving towards one that focuses on existing buildings for sustainability. Building renovation projects have attracted the attention of the construction industry. Still, there are many problems in the implementation process, such as many existing restrictions, incomplete functions, and low user satisfaction. In the traditional building renovation project, because the client does not fully understand the designer's intention and cannot participate effectively, the design process is modified repeatedly, and the efficiency is low (Zhu, Fukuda & Yabuki, 2019). Previously, stakeholders used technical drawings as a communication medium during this consultation process. But it is difficult for non-professionals to understand the detailed content. Also, models and drawings do not convey information about the project's scale, detail, and spatial perception. Information technology offers new potential for civic engagement in building renovation processes, such as Extended Reality (XR). XR technology is the collective name for all immersive technologies that merge physical and virtual worlds (Lo & Schnabel, 2020). XR technology allows users to perceive the scale and details of three-dimensional space as if immersed in an actual area. However, the main problem with using XR technology as a participatory design platform is that virtual operation is not friendly enough for non-professionals, and the technology of multi-platform sharing is still immature. Considering the inadequacies of virtual technology, we need to find a more intuitive way for users to communicate design ideas.

The physical model, as a simple input method, is a solution. Tangible User Interfaces (TUIs) are characterized by manipulating design variables with simple physical models and visualizing the results, such as "clay tables "and "sensetable "(Ishii et al., 2004; Patten et al., 2001), to facilitate communication among multiple people. However, these platforms can only display results with a screen projection and cannot provide an immersive experience. Välkkynen et al. (2013) used AR applications to enhance the realism of displayed views. Its TUI portion consists of 3D printed physical markers and an interactive desktop map. The results are viewed in AR, presenting similar problems as the previous example. There are relatively few studies on the combination of tangible model and XR as a participatory architectural design tool, especially in projects such as the renovation of old buildings that need to meet owners' needs to a great extent.

To achieve a better participatory renovation design process, we combined XR technology with a tangible model for testing as a design tool. From the aspects of immersive on-site design, the interaction between real and virtual scenes, and a simple, tangible model setting, the paper summarizes the participatory method conducive to the renovation of old buildings and proposes a future improvement direction. The participatory design method using XR technology and a tangible model will provide a convenient forum for renovating old buildings that designers and stakeholders participate in collaboratively.

RELATED WORK

Development of old building renovation

Building renovation refers to repairing existing building parts to improve their quality of use and functionality to save environmental resources. Renovation based on retaining the original value of old buildings and prolonging their service life can alleviate the predicament of urban land shortage and promote the sustainable development of the environment. Therefore, the renovation of old buildings has become the industry's focus in recent years (Gao, 2020). In the 1990s, the renovation of old buildings mainly met people's safety needs through structural reinforcement. After entering the 21st century, sustainable development has been deeply rooted in people's hearts, and research has paid particular attention to improving energy efficiency and saving energy. At the same time, research related to building renovation is becoming more critical, such as the individual needs of owners for renovation, the cooperation of stakeholders, and social benefits (He et al., 2021). This suggests that building renovations are shifting towards a multi-faceted, multi-participatory model.

There are many restrictive factors in the renovation of old buildings at this stage, and it is difficult for traditional design patterns to solve these difficulties effectively. The complexity involves political, cultural and economic factors and requires the government's macro-control and comprehensive public will to alleviate the contradiction to a certain extent (Gao, 2020).

Most traditional building renovation processes rely on professional drawings for communication. However, the information conveyed by the two-dimensional drawings is limited, and even there is distortion, and the accuracy is not high. Designers cannot present project information to users entirely and better, nor can owners clearly express their design intent. Communication barriers between users and designers significantly limit non-professional participation in the design, resulting in inefficiency and waste of resources in renovation projects.

Application of XR in participatory design

With the development of computer graphics technology, hand-drawn sketches have been replaced by digital media technology. Such technologies started in 2D images and 3D models and, more recently, in immersive and interactive environments such as virtual reality (VR), augmented reality (AR), mixed reality (MR), and extended reality (XR), which integrates VR, AR and MR. XR technology enhances the "reality" to immerse users in an artificially created world. These immersive technologies can display additional information in the real world, project information realistically (including accurate proportions, materials, sensory experience, etc.), and help users understand design solutions (Lo & Schnabel, 2020). Kwiecinski, Markusiewicz & Pasternak's（2017）research uses cameras and AR trackers to capture objects and then generates geometric shapes defined by Grasshopper, which are superimposed on real-world images to help users understand. Mixed reality (MR) fuses the real and virtual worlds, enabling 3D visualization in the field. Yda et al. (2021) developed a design tool, "*HoLoDesigner*". With this participatory design platform, users can freely express their ideas for community space design by placing prepared 3D furniture models into actual scenes.

However, there are many problems with Extended Reality as a tool for participatory design.

- User operation is complex. The current virtual interface is still very unfriendly to non-professionals. Even strict instructions often occur.
- The interaction is not natural. Complicated handles and gestures still limit participation by non-expert users.
- Complex 3D scene modelling. Even MR can visualize the live environment in 3D. However, many 3D models still need preparation, which is cumbersome (Yda et al.,2021).
- Not conducive to multi-person communication and collaboration. XR tools do not yet allow users to share the experience of a virtual environment.

APPLICATION OF VIRTUAL TECHNOLOGY + TANGIBLE MODEL PLATFORM IN PARTICIPATORY DESIGN

Physical models have always played an essential role throughout the design process. Such models help non-professionals analyze and understand abstract content and communicate design ideas intuitively. Tangible models, combined with digital presentation tools, attempt to bridge the gap between the real and virtual worlds and provide intuitive, visual collaborative design (Schubert et al.,2015).

Tangible User Interface (TUI)

Initial hand-drawn sketches and physical models are easy communication tools, but they convey less information. Tangible user interfaces are the primary form of integrated digital interface and physical model design tools for interactivity and more functionality. "*URP*" provides users with digital shadow and wind simulations in urban environments. The results are projected visually on the tabletop by moving the model with the optical labels (Underkoffler and Ishii,1999). Dalsgaard & Halskov (2014) intuitively display abstract information on tangible objects, which helps non-professionals understand project information. When the physical model is placed on the table, information such as elevation patterns and geographic data is projected onto the object. "DeepScope", developed by MIT Media Lab, consists of a generative neural network (DCGAN) and a TUI. The streetscape visualization will help users better understand the project (Noyman & Larson, 2020). "*CityMatrix*" supports real-time performance analysis of user decisions. Their breakthrough introduced machine learning into the analysis module, which improved the speed of simulation analysis, realized real-time system feedback and assisted users in decision-making (Zhang et al., 2018). Nevertheless, these TUI systems usually consist of physical desktops, projectors, and cameras. The equipment is complex and costly, and the display effect is not realistic enough.

Existing XR+ tangible model platform

In recent years, some researchers have used immersive technology as a display tool of a digital model to optimize the output effect of design results. For example, in "*sketchand+*" (Seichter, 2003), the physical model is the basis of the scene. Using the head-mounted display, you can see the three-dimensional virtual model. Silcock et al. (2021) created a low-tech AR environment. By overriding the virtual buttons, new house types are created. Their system also supports using graphical user interface (GUI) sliders to simulate real-time lighting. Schubert et al. (2015) propose the possibility of incorporating data analysis and simulation into mixed reality views to inform design decisions and creative thinking. This design platform is easy to input while enabling real-time experience in a realistic environment, taking the development of participatory tools one step further.

The advantages of the XR+ tangible model platform used in participatory design

1. Simple operation mode. Intuitive tangible objects allow users to interact more naturally in the participating system. Using physical models as input instead of user instructions to operate in a virtual environment may reduce the participatory challenges associated with complex system operations.
2. Facilitate multi-person collaboration. Through the physical interface, design ideas can be presented directly on site. Designers can use familiar tools and methods to negotiate, and non-specialists can express their opinions. The 3D model can be seen simultaneously in the virtual scene, which helps the participants understand the project information and make decisions.
3. Connect the real and virtual worlds. The XR+ tangible model design tool provides seamless coupling between the natural environment and the virtual scene. Changes in the physical model (position, shape) can generate virtual variants in real-time. This connection eliminates the need for complex modelling activities, reducing costs. Different ideas are tested in physical and virtual environments, fostering dialogue and design exploration among participants.

Using XR+ tangible model platform in renovation design

The renovation design is to modify and replace the original object. Compared with new construction projects, more consideration needs to be given to the renovation needs of the owners, so it is necessary to use the most straightforward way of physical model so that non-professional users can express their opinions. Intuitive physical models also provide opportunities for on-site communication with designers. In addition, the renovation project already has a certain degree of design basis and has on-site environmental conditions. Therefore, there is a need for a platform that can operate in a natural environment, which also helps non-professionals feel the accurate scale and details of the space.

Therefore, this study aims to develop a design platform that combines XR with a tangible model to facilitate user participation in renovation design. The platform is designed to enable 3D visualization of the live environment and help participants understand abstract project information. In addition, it supports real-time interaction of virtual scenes and physical models, assisting users in communicating their ideas in a fun and straightforward way.

METHODOLOGY

User needs

In this paper, a case is used to test the virtual-real interaction design system to assist the public in participating in the renovation. This article selects an old house from the 00's as an experimental project. The building is located in Shaowu City, Fujian Province, China. The residential area is 99 square meters (Figure 1).

Figure 1
Project site photos

The residence was initially vacant, and the owner intends to adjust the original layout and move in this year. The owner is a family of four. The parents are middle-aged people working in the local area. The two daughters are students studying in universities in other cities in China. The two daughters are away all year round, and they have a grandma who sometimes stays for more than ten days. The owner hopes to adjust the layout of the dining room, small bedroom, and main bathroom to meet the current needs. So we designed a participatory renovation experiment to assist the owner in the decision making.

According to the owners' needs, we have preconceived several possible layout situations for users. Although the exact wall position and furniture arrangement still need to be discussed, these can already express the user's transformation intention and represent the real possibility (Figure 2).

Prototype implementation

In the choice of XR equipment, Microsoft HoloLens 2 is used. Its unique spatial mapping can fuse virtual models and natural environments. It can also create an interaction between virtual and real, providing the basis for the interaction between physical and virtual models. When users wear HoloLens, they can not only see the mapped virtual model, and its translucent lenses also allow users to see the scene environment and the physical model placed on the scene, which is beneficial for participants and designers to communicate and collaborate on the scene.

The game engine Unity3D is used to develop the virtual scene. For the part of the physical model connected to the virtual model, we chose radio frequency identification (RFID) technology. RFID tags can be attached to any object, and when an object with an RFID reader approaches the tag, the corresponding information can be read or queried. It can also identify multiple tags simultaneously without interfering with each other.

Development process

Figure 3 shows the system structure of our participatory design tool. The user manipulates the solid model as an input method for the design variables. For the tangible model part, we prepared a 1:20 manual model. The hand-crafted model fully expresses the layout and proportion of the existing space, which can be quickly understood even by non-professionals. This handmade model includes the walls that need to be preserved in the existing house, as well as 4 wall models for the user to choose and place. In addition, we also attached the reader at the bottom of the pre-set position of the manual model, and attached the RFID tag under the 4-piece wall model. This reader is connected to the Arduino electronics board, which sends signals to Unity to

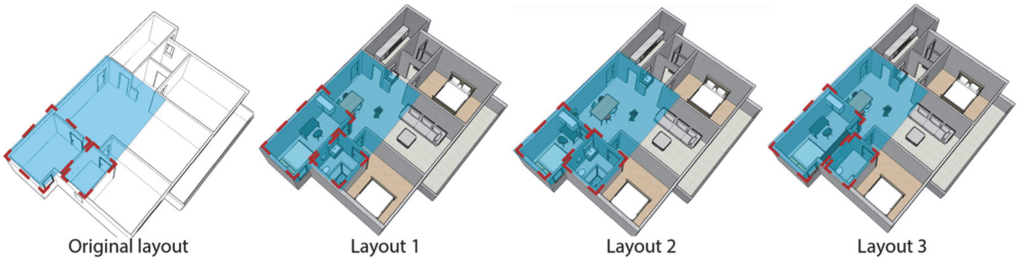

Figure 2
Layout modes provided

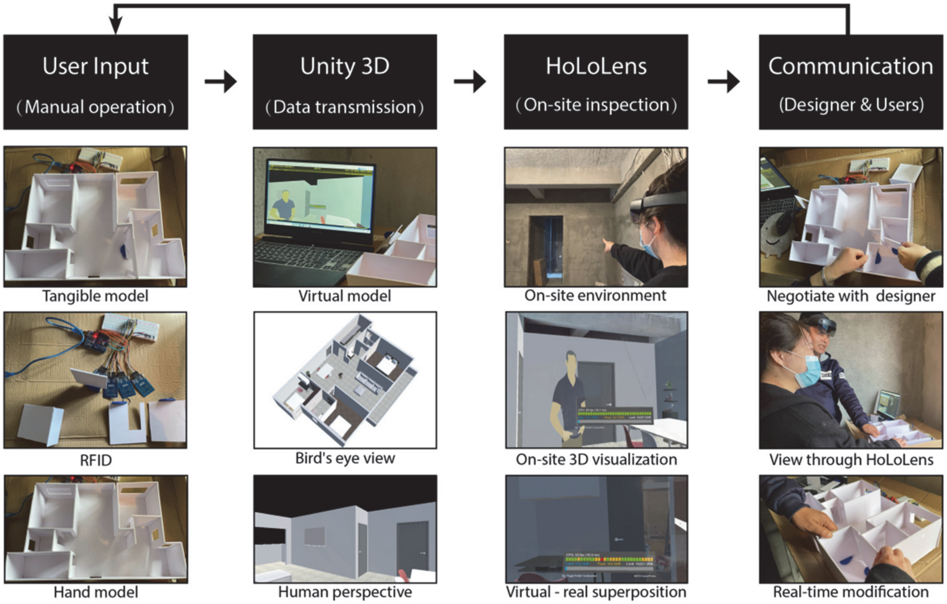

Figure 3
Virtual-real, interactive, participatory system structure

display the corresponding digital model in the 3D Unity environment. When users wear HoloLens glasses, they can see the virtual model corresponding to the physical model. Designers and participants can communicate and collaborate around the mockup.

In the virtual scene, we also prepared some furniture models. We are equipped with corresponding furniture layouts for these four walls and the corresponding space to assist users in judging the proportion and size of the area. Users only need to place solid walls on the base of the manual model, and they can see the digital models composed of these walls and the corresponding furniture models in the virtual scene. This design tool uses the physical model as an input for user engagement to trigger changes to the corresponding virtual model. Finally, the virtual-real superimposed scene is used as the output method of the design effect to realize the interaction between the virtual and the real. Users participate in the design through this virtual-real linkage.

Results and analysis

After the experiment, we conducted interviews and questionnaires with four members of the owner's family. We invite users to rate the spatial satisfaction of each layout (out of 5). Table 1 shows the average score of the four users with respect to the space satisfaction of each layout. For small bedrooms, users said that in layout 2 and the original layout, the room area is too small. The spatial experience is more oppressive, and the space is more crowded after the furniture is arranged. The small bedroom scores for layouts 1 and 3 show that changes in the size of the bathroom have little effect on the space of the small bedroom. For the main bathroom, users are more satisfied with the large bathrooms in layout 1 and layout 2. Shower facilities cannot be arranged in the small bathroom. For the dining room, the scores

Table 1
User
Satisfaction
Score

Layout		Layout 1	Layout 2	Layout 3
Score	small bed-room	3.75/5	2.5/5	3.5/5
	main bath-room	4/5	4/5	2.25/5
	dining-room	2.5/5	3/5	2.25/5
Total score		10.25	9.5	8

were not much different. Users also said that the size of the dining rooms could meet the use requirements. The dining rooms in layouts 1 and 3 are the same, but the scores are inconsistent, resulting from the user's consideration of the overall space. In the end, the owner, combined with our score table, and the experience of personally participating in the design and understanding of the space, decided to take layout 1 as the design intent for the renovation.

We also interviewed whether our design tools could help them make renovation decisions. They said that when they wear HoloLens and walk around the room, they can see the corresponding virtual model and the actual scene around them in real-time. The virtual models are superimposed on the live environment at an accurate scale, which can help them understand the abstract spatial layout exactly. With the mockup, they can position the walls themselves and change the room's design.
It is straightforward for non-professionals. Correspondingly, they can also see the change in the field immediately through the virtual model projected by the HoloLens, and make comparisons between different layouts (Figure 4). This saves the time and cost of actual construction and helps users make renovation decisions.

Figure 4
Experience and comparison of different layout modes

DISCUSSION

This experiment aimed to increase user engagement in the renovation design. We will discuss the immersive on-site design, the interaction between real and virtual scenes, and the simple, tangible model setting and summarize the participatory methods conducive to the renovation of old buildings.

Immersive on-site design

We offer users the opportunity to design in a natural environment. Regarding the question "Do you agree that the superimposed scene of virtual and real makes the design scheme easy to understand?" the owner believes that the actual scene can increase the understanding of the abstract space. Previous studies have attempted to add immersive technology at the output to enhance users' understanding of professional solutions. However, the previous XR and physical interaction platforms, such as "*CDP*" and "*sketchand+*", can use XR technology to view virtual models, but they lack immersion and cannot be designed in the environment of the design site (Schubert et al.,2015; Seichter,2003). However, our research goes one step further. The existing on-site environment of the renovation project, and the virtual model representing the design intent are superimposed on it at a real scale, which can help users understand different design schemes. As this is ongoing research, the virtual variant part is still relatively rough in production, and the authenticity is not enough. We will continue to refine the virtual model and enhance the fidelity of the overall scene.

Interaction between real and virtual scenes

Although we cannot fully realize the linkage reaction between the physical model and the virtual variant, most users are very interested in this interaction. In the question "Do you think this virtual-physical design system helps express your design intent?" the owner stated that with the help of handmade models, they could easily change the spatial layout. Through the linkage changes of virtual scenes, participants can compare different spatial arrangements in real-time to help them make judgments. This is impossible to achieve in actual construction. Previous work has also attempted to create better connections between physical and virtual models, but the interaction methods are still relatively simple. Like "*ARTHUR*", they mostly allow users to manipulate virtual models through placeholders and gestures (Penn, 2004). Our system sticks RFID tags on the physical model, and the corresponding virtual model and the furniture arrangement can be popped up in the virtual environment. This undoubtedly increases the possibility of a close connection between the virtual and the physical. The current limitation is that this interaction between virtual and real still cannot meet the actual needs of users. Future research should strive to break through the restrictions that users cannot move models at will, and display structure and equipment information to meet more renovation needs.

Simple, tangible model setting

Our tangible model part is relatively simple to set up and relatively easy to operate. We asked, "Does the mockup help express your design intent?" and the owner agreed. This is because the user can participate in the design simply by "placement" of the solid wall. Most of the previous research used TUI as the physical part. It was necessary to set up a multi-point control table, arrange cameras, projectors and many other devices to realize the transformation from physical to virtual (Schubert, Riedel &Petzold, 2013; Dalsgaard & Halskov, 2014; Zhang et al., 2018). These all increase the preparation time and cost. Our tool does not require much physical model. Just stick RFID tags on arbitrary objects. This undoubtedly adds more possibilities for future work. Eslam et al. (2018) utilized 3D printed translucent objects as physical parts of historical models. When the tag senses the reader, the light will illuminate the object. This realizes the two-way interaction and feedback between the virtual and the real. We have only met the requirements of the simplified physical device and simple operation in this study. In the future, with the increase in design requirements, there are two improvement directions:

- Enrich the form of the physical model, just like the physical models of different historical periods displayed by Eslam et al. (2018), supplemented by lighting effects, intuitively inform users of more information.
- Implement virtual-entity two-way interaction. In the future, we will try to add virtual operations to cause physical interactions to convey more information.

CONCLUSIONS

The tight connection between the physical model and the virtual scene will allow people to better participate in the renovation process. Through a residential renovation experiment, the results prove that the virtual-real interaction system can improve the effectiveness of public participation in the renovation. Simple manipulation of the physical model allows users to design in a 3D environment on-site rather than expressing design intent through traditional professional drawing files. This system supports real-time interaction between virtual scenes and physical objects, providing an intuitive display and interaction method to compare design proposals, allowing professionals and non-professionals to collaborate and communicate. This study is a first step towards addressing this problem, which still has some limitations due to interface and hardware limitations. Nonetheless, we believe our findings may facilitate user involvement in the early design process of renovation projects.

Future work will include:

1. Increase the interactivity between virtual and physical. Optimize virtual and physical interaction systems to increase user engagement. For example: adding more interactive ways (zooming, moving the model), adding annotation tools where users can provide feedback and suggestions, developing virtual-physical two-way real-time feedback capabilities.
2. Collaborative design with the BIM platform. The BIM platform can integrate comprehensive details of construction projects. Integrating BIM data into participatory design systems can provide more realistic solutions for complex renovation projects.
3. Intelligent tools such as genetic algorithms and machine learning to rapidly process large amounts of data， applied to participatory systems, can assist users in making design decisions (Noyman & Larson, 2020； Zhang et al., 2018).
4. Remote Communication. Expand the network protocol to enable multiple XR devices to share the identical hologram to support multi-user remote collaborative interaction.

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