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Interactive Design of Structural Membranes Through Mixed Reality

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Abstract

Membranes are frequently used in architecture for their light weight and rapid construction time. However, the elastic nature of membranes makes it difficult for humans to predict and apprehend their shapes. Recent advancements in digital technology have enabled the prediction of membrane behavior through computation. Furthermore, Mixed Reality (MR) technology has made it possible to display these results immediately at full scale and overlaid with the real environment. Based on this background, we have developed an MR tool to assist in designing membrane structures. Taking advantage of MR to visualize 'invisible' information, the different parts of the membrane are colored based on their state of extension. This allows for checking whether the membrane is appropriately stretched and verifying construction feasibility. In addition to supporting designers by displaying hidden information, the tool enables users to modify the anchor points of the membrane in the MR environment. Three methods of interaction have been tested for this operation. First, anchor points are grabbed by the designer with their fingers. Second, the points can be modified on a scaled model displayed in MR that is synchronized with the full-scale display of the membrane. Third, the anchor points are set with a laser distance meter to improve accuracy and range. Ultimately, the results of our experiments showed that changing the method of interaction between human and virtual models had a significant influence on the user experience.

Keywords: Mixed Reality, Membrane Structure, Flexible Material, Form Finding

1. Introduction

The Concept of Mixed Reality (MR) presented by Milgram in 1994 [1] is overlapping digital and real-world information and can be understood as a continuum of Virtual Reality (VR). Early research on MR technology for architecture have been conducted in 1996 by Webster et al. [2]. They have developed prototypes to show components of a building which are hidden behind finishes and to assist assembly of space frame structures. Previous research from Kaneko et al. [3] has shown that MR technology is effective in the construction field at the design, consensus building, construction, inspection, and management stages.

In recent years, several research teams have focused on leveraging MR to support construction processes. As a result, complex 3D shapes could be assembled without the need for 2D drawings [4]. For example, Jahn et al. [5] have constructed a pavilion consisting of steel rods that had several filleted bends and linear sections. Bending and assembling these rods were done with the help of MR navigation. Using MR, Goepel and Crolla [6] made a pavilion with bamboo. This research has dealt with bamboo, flexible material like membranes, but they have not attempted to create precise instructions for assembling bamboo. Rather than predicting behaviors of bamboo accurately by digital simulations, they have relied on the worker's intuitive response to material behaviors.

Regarding the use of MR to support design activities, there are not as many studies as for construction activities. Major applications consist in reviewing static models and few studies have developed tools that enable interactive design through MR. HoloDesigner has been developed by Dan et al. [7] and allows users to arrange street furniture for park design. The interaction can be performed through different functions such as: model adjustment, model placement, model deletion, spatial distance measurement, and model materials selection. Another application is Mindesk [8], a 3D Computer Aided Design (CAD) software with a VR interface where users can do 3D modeling.

Also, there are many studies which have validated the effectiveness of MR in the field of education. For example, Tang et al. [9] has shown that in apprehending the structure of the engine, learning with a virtual 3D model in MR has been effective compared with the traditional way of learning with 2D drawings on a textbook. Another research is conducted by Zhao et al. [10] and they have developed an MR tool to visualize the real-time data of indoor illuminance obtained by sensors. When users have changed designs of the shading of the room, they can learn how the design has an influence on indoor illuminances.

As for membranes, Valentini et al. [11] have constructed a virtual membrane with the real-time simulation that can be deformed interactively by the action of the user in VR. Unlike our research, they have aimed to construct an accurate simulation of membranes and interaction system which have made users feel as if they were touching a real membrane and they have not intended to design the form of membranes. It seems there are no current tools for designing membranes available in MR. In addition, while their use has been increasing in recent years [12], many difficulties remain with regards to their design and construction. While they offer quick installation due to their light weight, it is difficult to predict their doubly-curved shape accurately because it is the result of mechanical balance and deformation. With the advent of digital technology such as 3D CAD and physical simulation software, the situation is improving. However, displaying 3D models on the flat screen of a computer makes it difficult for human to apprehend their global shape as well as the space underneath. Consequently, MR may offer an effective alternative for grasping the complex geometry of membranes by making it possible to experience and check the space at full scale. The main hypothesis of this research is that an MR-based membrane design tool would facilitate the design of membrane structures and lead to the creation of new architectural spaces. This study aims to gain insights into the development of the tool.

2. Method

Figure 1 shows the devices and software we used to develop our interactive design tool for structural membranes. Form-finding is conducted using Kangaroo2 (K2) and K2Engineering (K2E) within Grasshopper, Rhinoceros 7. Unity acts as a relay, exchanging 3D models or some digital information with Grasshopper and the MR headset. In this study, the head mounted display (HMD) is the “Meta Quest 3" developed by Meta. While most previous studies have used see-through HMDs such as the “Hololens(2)” from Microsoft in which users perceive the real environment through a transparent lens, the Meta Quest 3 is a pass-through MR device meaning images are captured in real time by a camera and displayed in MR. Therefore, this research is also meaningful to verify the usability of pass-through type HMDs in the field of architecture.

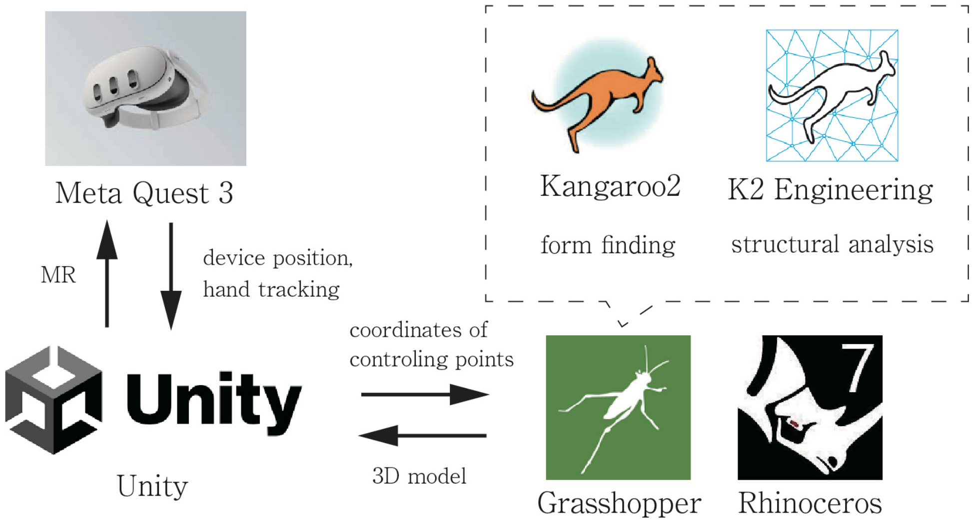

Figure 1: Devices and software organigram.

The developed tool takes advantage of MR to visualize 'invisible' information by coloring the parts of the membrane based on their state of extension (Figure 2). Red indicates over-extension, white indicates proper extension, and blue indicates insufficient extension. A color code allows users to check whether membrane stress is appropriate and whether the construction is feasible by making sure there are no red parts. Making the most of parametric design, the original shape of the membrane before stretching can be changed while conducting physical simulations.

Figure 2: membranes are color-coded to three colors

Concerning the user interface, the shape of the membrane is operated by moving the anchor points of the model in MR. The tool gives the possibility not only to review the design, but also to change the design by moving anchor points. Designing in MR allows different iterations to be tested. Ultimately, this leads to more optimized and more original forms that exploit the membranes flexibility. Three methods have been developed for this operation since it is expected that the user experience and design is likely to be influenced depending on the user interface.

The first method allows users to grab the anchor points directly by hand in real space. Cubes are displayed at the anchor points of the digital model and can be catched by hand (Figure 3). This method relies on the hand tracking function in Meta Quest 3. As an alternative, controllers can also be used instead of hands. If points are out of reach, they can also be remotely grabbed or moved using virtual ray beams emitted from the controllers.

With the second method, users grab anchor points on a scaled-down model displayed in MR that is synchronized with the full-scale display membrane (Figure 3). The smaller model includes both the membrane and its close environment. As for the first method, anchor points can be picked up and moved by hand or controllers. Note that the anchor points of the full-scale model can also be moved in this variant.

In this method, the problem of spatial alignment between real and digital space arises. In most previous studies, spatial alignment has been done by placing a QR code in real world. However, markers do not necessarily need to be placed in the real space; Since the spatial alignment is a matter of the origin position and the rotation of coordinate space, as long as the coordinates of the virtual object can be tracked, you can use virtual objects as origin and reference point to define the rotation of the space.

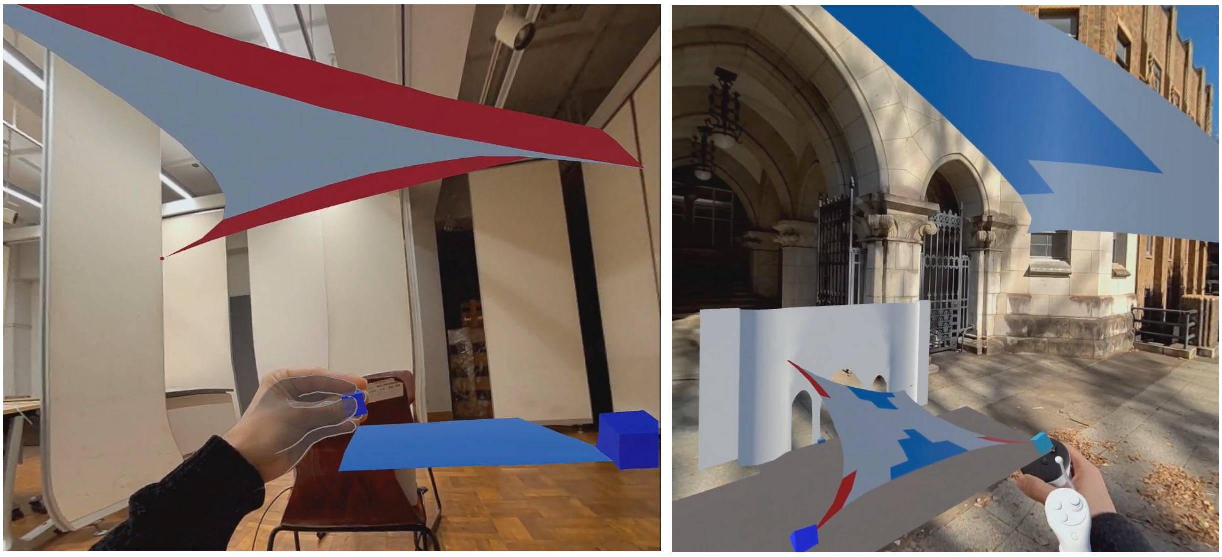

Figure 3: First (left) and second (right) method

With the third method, users can set anchor points at long range using a laser distance meter. To compute the 3D coordinates of the anchor point, the distance and direction of the laser are needed. The distance is directly obtained from the laser distance meter while the direction is obtained by aligning the laser with one of the HMD controller. To keep both of them parallel, a custom encasing was 3D-printed (Figure 4).

Figure 4 : 3D-printed laser distance meter and controller container

In the development process, **Experiment 1-3** has been conducted first, followed by **Experiment 4** to gain insight into the functionality implemented in this tool.

3.1. Experiment 1

In K2 and K2E, physical simulations are performed by setting the load at each vertex and the stiffness at each edge of the meshed membrane as parameters. For the validity of the physical simulation, it is important that the parameters are realistic. For this purpose, stretching experiments are conducted to investigate the mechanical properties of the membranes.

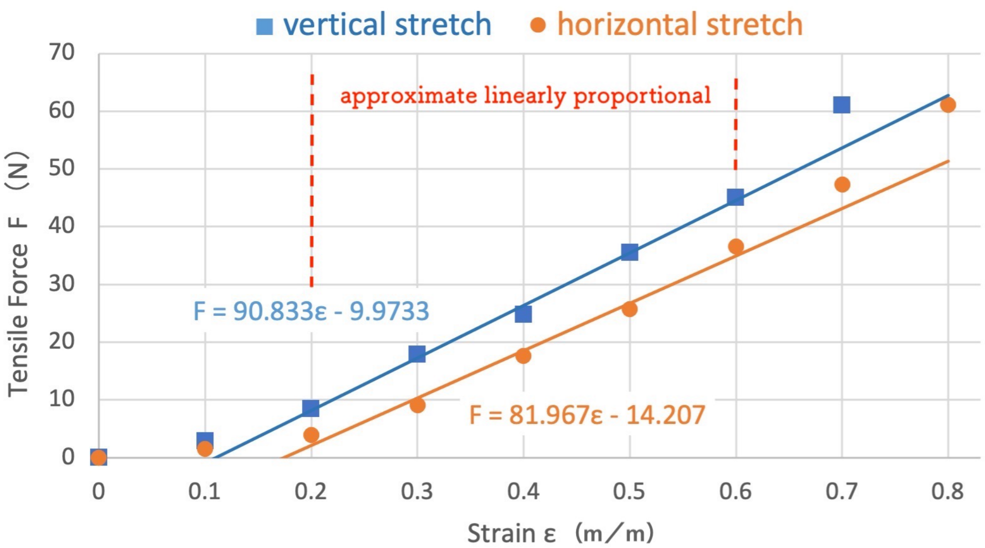

Figure 5: Graph summarizing stretching experiments

Tricot cloth (82% polyester, 18% polyurethane) has been used in this experiment because this cloth can be stretched well by human power. The weight per square meter was 0.205 kg/m2. The results of the stretching experiment are shown in Figure 5. It has been found that the tensile force and the strain are not linearly proportional, but exponentially related.

Figure 6: Tensile Force is measurement by pulling the each side of the cloth

Since K2 and K2E are based on Hooke's law σ = Eε, these results cannot be used directly. From Figure 5, a proportional relationship can be approximated in the range of strain ε from 0.2 to 0.6 m/m. Consequently, this range was set as the appropriate extension range. An approximate straight line in the proper extension range was obtained by the least-squares method, and the stiffness was calculated from the slope of this line. The second term of the equation was handled by assuming that each edge was pretensioned. It is expected that the simulation will be realistic within this range. Since the ease of stretching differs between the longitudinal and transverse directions, the average value of both has been used for the physical simulation. Parts of the membrane stretched in this range are displayed in white, if extension rate is under 0.2 m/m, parts are displayed in blue and if over 0.6 m/m, parts are displayed in red, and the construction is regarded as difficult.

3.2. Experiment 2

Next, to confirm the accuracy of the physical simulation, we have conducted Experiment 2 while comparing the digital model we have designed in MR with a real piece of fabric. The membrane has been made from the same material as the one used in Experiment 1 with a size of 1.5 by 3.0 meters. Its shape has been controlled by moving the four anchor points both in MR and in the physical experiment. Additionally, when constructing the membrane, the MR-displayed membrane has been used as guidance.

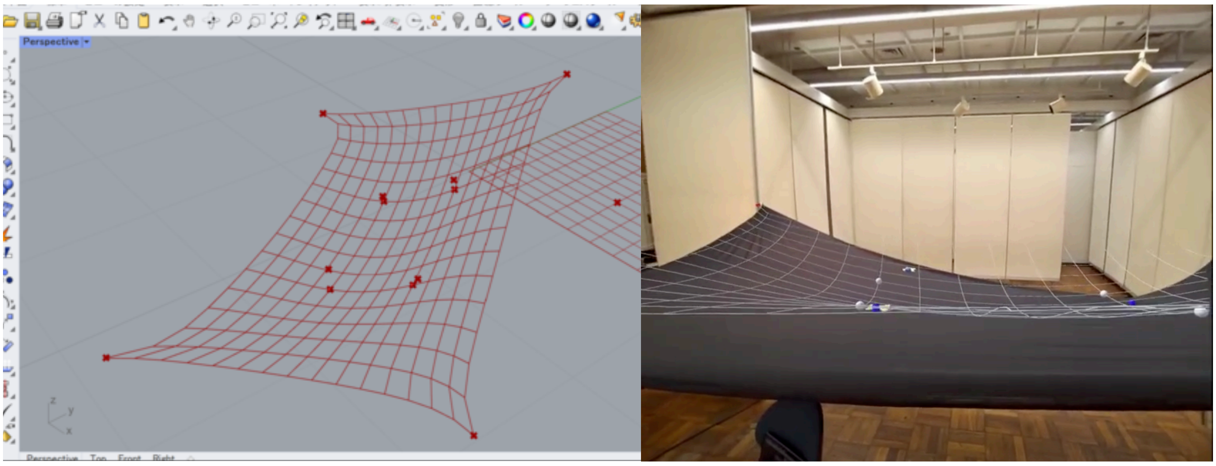

Figure 7: White spheres are 4 representative points on the 3D model (right) displayed with its wireframe, and blue cubes are superimposed virtual models onto the marked locations. Distances between the set of two points are measured in Grasshopper, Rhinoceros 7 (left)

To measure the difference between the physical simulation and the real membrane, we have compared the coordinates of four representative points of intersection obtained by dividing a rectangular membrane into three parts in the vertical and horizontal directions respectively (Figure 7). To obtain the coordinates of the four points of the real membrane, the four representative points were marked in advance on the membrane, and after construction, the coordinates were obtained by moving and superimposing a digital cube of 10 mm per side prepared on MR onto the marked locations.

This experiment has been conducted 4 times. Two out of four times all 3D models of the membrane have been displayed in white. The other 2 times, the blue portion has remained. The results have shown that in the former two times, the average distance of the set of two points has been 47mm and 56mm, while in the latter two times, 140 mm and 111 mm. These results show that the error is large when the tensile force is not sufficient and the membrane is slack, and the error is less when the extension is in the appropriate range. This is thought to be due to the setting of physical simulation in which the tensile force and strain are approximated as having a linear relationship. Potential sources of errors include (1) the accuracy of the physical simulation, (2) the tolerance of the MR display, (3) accuracy of the manual measurements while overlapping the marked locations and the measurement cubes, (4) the accuracy of the construction, and (5) the accuracy of the marking.

3.3. Experiment 3

The third experiment has aimed at testing the accuracy of the third method of interaction. The procedure of the third method is a three-step process. First, determine the location where the anchor point is to be placed. Second, a distance meter set with a controller is pointed at that location and aligned with the laser pointer emitted from the distance meter. Finally, the distance is measured, and the direction is obtained from the controller while the anchor point is placed. The following is an explanation of the methodology of the experiment.

First, a target has been prepared, and a mark has been placed on it to align the laser pointer. Next, as in Experiment 3, a digital model of the cube with 10 mm per side has been manually placed as a reference at the location of the mark. Then, an anchor point has been placed at the mark through the procedure mentioned, and the distance between the anchor point and the reference cube has been measured from the coordinates of the reference cube to verify accuracy (Figure 8).

The test has been conducted at distances of 3m, 5m, and 10m. It would have been interesting to conduct experiments at longer distances. However, 10 m was the maximum distance for moving freely in the space with the space settings of the Quest 3. Ultimately, after getting 5 values for each distance, the average was 65.4mm at 3 m, 125mm at 5m and 162mm at 10m. As for the previous experiment, those results include (1) errors in the controller, (2) errors in the laser distance meter (3) errors in MR display, (4) errors in not completely overlapping the marked locations and the measurement cubes.

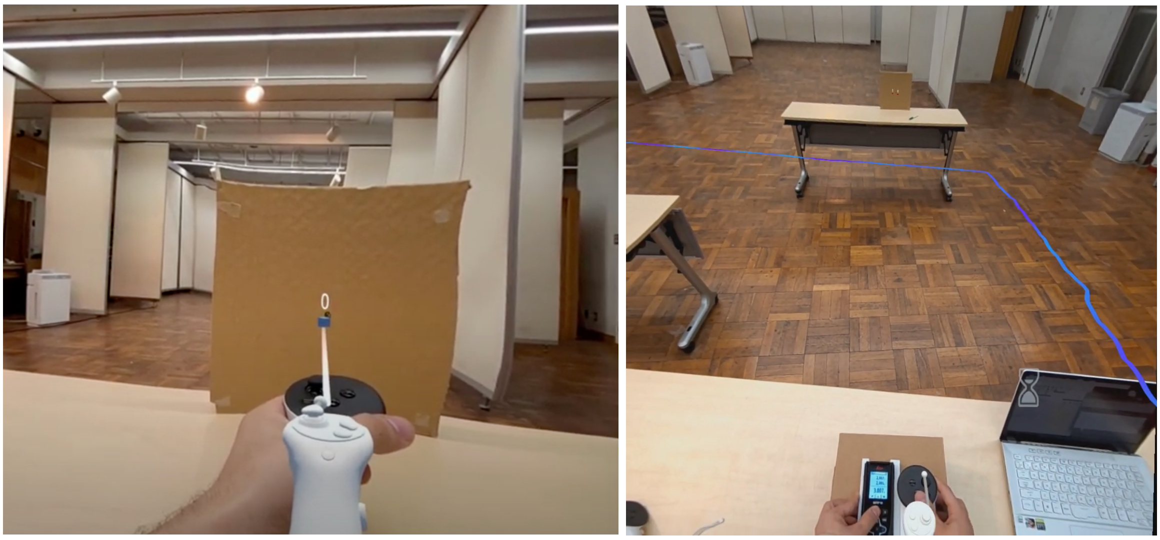

Figure 8: Condition of experiment 3. Distortion of the image can be seen in the left picture

It has been confirmed through Experiment 2 and 3 that Meta Quest 3's pass-through images can be subject to lags and distortions at the edges of view. Proper lighting is also crucial as noises can occur in the image when the space is dark. Conversely, it is difficult to see the laser pointer used in third method when the space is bright.

3.4. Experiment 4

To gain insight into the developed functionality, three tools with different operation methods have been prepared and several subjects have been asked to use these tools. Tool 1 adapts the first method of manipulation, Tool 2 adapts the second method and Tool 3 adapts the second and third method. After the tests, the participants have been interviewed about their experience with tools. The subjects were 6 architecture students, 4 males and 2 females. They had never experienced VR or MR before this experiment. Before the experiment, we have taught them the necessary operating procedures.

Subjects have been asked to design a membrane structure that would satisfy some given conditions. The conditions in the experiment have been set based on the assumption that the design plan should be considered in relation to the site and surrounding environment, which is required in architectural and urban design.

Subjects using Tool 1 have been asked to put on a membrane in real after they designed. In addition, there have been a requirement that membrane do not hit set obstacles during construction.

4. Result

In the first experiment, stretching experiment has been conducted for physical simulation. In the second experiment, the accuracy of the physical simulation has been verified. In the third experiment, the accuracy of the laser distance meter and controller has been checked.

Subjects using Tool 1 in which users have manipulated anchors by hand have appreciated that MR has allowed them to experience the space beneath the membrane. They could check whether the requirements have been met by MR and they have succeeded in putting on the membrane without hit. So, it has been suggested that the level of error, as obtained in Experiment 2, is sufficient for MR to confirm the shape of the membrane. However, they also have commented that it has been difficult to grasp the overall shape of the space because they have had to enter the space. One subject has been unable to see the full extent of the membrane and twisted the membranes by inadvertence.

Subjects using the second interaction method have designed larger membrane model than Subjects using the first one. Furthermore, they have highlighted that they could better grasp the overall shape with the scaled-down model and better experiment with the full-scale model. On the other hand, it has been pointed out that there might be an error in the MR display, and that there could be discrepancies between models and reality. They have also found that remote control by the controller's ray has become more difficult at distances greater than a dozen meters.

Subjects using Tool 3 have said that they could place anchor points mostly where they want to place, so the accuracy obtained in Experiment 4 suggests that it is acceptable for use. Also, they have designed larger membrane than in subjects using Tool 1.

In common with three tests, subjects have noted that there is the lag of the MR images, the shading of the membranes differs from reality, so that the membranes displayed by MR do not feel like real membranes, and that the larger the membranes, the less accurate the scale seems to be.

5. Conclusion

The obtained results have given insights into the performance of the developed tool and in the kind of interaction that is required to design membranes with MR. One test subject has commented that it has been difficult to grasp the overall shape of the membrane when designing it from inside. It suggests that designing membranes would require a bird's-eye viewpoint. On the other hand, since entering the design space is also effective in learning spatiality, it is desirable to have a tool that allows both immersion and a bird's-eye view. This has been supported by the impressions of subjects who have manipulated both scaled-down and full-scale digital models.

Also, the reason why digital models of membranes "do not feel like membranes" may be due to the difference in resolution between the real environment and the digital model. In MR, the digital model is an abstraction, while the surrounding environment, the real space, is not. Therefore, the ability to "compensate for low-resolution objects with imagination" that functions in model studies may not be as effective as it is in MR. Therefore, for MR to become a technology that truly integrates digital information with the real environment as its definition, it is important to acquire information from the real environment and feed it back to the digital one. For example, acquiring data about the real lighting environment could help determine the shading of a digital model.

Recently, detailed Building Information Model (BIM) of cities have started to be assembled. As data is becoming more available, these large 3D models could support the design of structures in MR. While BIM models can sometimes differ from reality, methods such as introduced in the third experiment of this paper would allow to harvest the benefits of MR combined with real-world feedback. Therefore, future research could focus on realizing real-time on-site design, in which design is performed while constructing a 3D model of the environment. Also, one of the subjects in Experiment 4 said that there could be discrepancies between models in MR and reality, and Mitterberger [13] pointed out that the accuracy of portable MR headsets is insufficient for some tasks. Therefore, future research could focus on realizing real-time on-site design, in which the initial design is quickly performed while constructing a 3D model of the environment.

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