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The Development of a Haptic Interface for Interacting with BIM Elements in Mixed Reality

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Abstract: Building Information Modeling (BIM) is widely used to efficiently share, utilize and manage information generated in every phase of a construction project. Recently, mixed reality (MR) technologies have been introduced to more effectively utilize BIM elements. This study deals with the haptic interactions between humans and BIM elements in MR to improve BIM usability. As the first step in interacting with virtual objects in mixed reality, we challenged moving a virtual object to the desired location using finger-pointing. This paper presents the procedure of developing a haptic interface system where users can interact with a BIM object to move it to the desired location in MR. The interface system consists of an MR-based head-mounted display (HMD) and a mobile application developed using Unity 3D. This study defined two segments to compute the scale factor and rotation angle of the virtual object to be moved. As a result of testing a cuboid, the user can successfully move it to the desired location. The developed MR-based haptic interface can be used for aligning BIM elements overlaid in the real world at the construction site.

Key words: Haptic interface, Mixed reality, BIM, Spatial alignment, Head-mounted display

1. INTRODUCTION

Various stakeholders are involved in a construction project, and the amount of information generated in each process is vast. Building Information Modeling (BIM) is used to efficiently share, utilize and manage this information [1-3]. BIM also improves the efficiency of construction projects in planning, design, prefabrication, and process management [4]. On the other hand, extended reality (XR) technologies are introduced to more effectively utilize BIM objects; especially, virtual reality (VR) has been applied to the training and education of construction workers because of the advantage that users can interact with virtual objects directly [5-6].

However, it is challenging to improve the proper field of view (FOV) and calibration between the actual world and virtual objects [7].

This study aims to develop a haptic interface system that allows users to interact with BIM objects in mixed reality environments to move them to the desired location, ultimately enhancing communication between a field worker and an office manager. This system allows head-mounted display (HMD) users to identify a virtual object with their finger and move it to the desired location in mixed reality. In this study, the system's applicability was verified for a cuboid. In order to move a virtual object to the desired position in mixed reality, several processes need to be undertaken, such as scaling, horizontal and vertical movement, and rotation. This study established this series of processes and elaborated each process.

2. LITERATURE REVIEW

2.1. Extended Reality Technologies

Recently, research has been widely conducted to utilize BIM design objects in XR [8-9]. Generally, XR technologies include Virtual Reality technology (VR), Augmented Reality technology (AR), and Mixed Reality technology (MR). First, VR is an artificial digital environment that completely replaces the real world. VR immerses users in a wholly artificial digital environment generated by a VR device such as VR headsets. On the other hand, in AR, users see and interact with the real world while digital content is overlaid on it. AR overlays virtual objects on the real-world scene. The best example of AR is Pokemon Go, a mobile game developed by Niantic [10]. It overlays virtual creatures on the screen of a smartphone displaying the real world. However, AR has limitations in that it has a limited range of fields. Finally, MR, the most recent development in reality technologies, not only overlays but anchors virtual objects to the real world. Users can interact with both the real world and the virtual environment. MR users remain in the real world while digital content is added to it, and the users can interact with virtual objects. The user can identify and manipulate virtual objects via the MR device.

Currently, spatial alignment technologies of virtual objects to the real world in AR and MR are being developed in various ways. The spatial alignment can be divided into a marker-based approach and a markerless approach. AR's main objectives are to analyze changes in the captured camera frames and correct alignment of the virtual object into the camera scene based on the tracking results. The marker-based approach provides accurate tracking using visual markers, such as binary markers or photos of real planar objects on the camera screen. The marker tracking approach is easy to use, and detailed instructions are not required for people who use it. On the other hand, virtual objects disappear when the camera is moved away from the marker. Scanning will not work if markers reflect light in certain situations [11]. Stigall et al. (2018) conducted a study to confirm 3D drawings in an AR using 2D floor plans as markers to provide a better understanding of building design in case of an emergency [12]. Al-Adhami et al. (2019) discussed the implementation of a marker-based approach for quality control based on experiments at actual construction sites [13].

The markerless-based approach works by scanning the surrounding environment, and there is no marker necessary to retrieve the virtual object from the database. The virtual object in this approach may not work in a certain context. For a better experience, it is required that the surface has a texture for computer vision to recognize it. Kalasapudi et al. (2014) validated the proposed change analysis approach between 3D laser-scanned point clouds and MEP components using the 3D laser scanning technologies [14]. Miyake et al. (2017) developed an AR system to visualize design projects of buildings using Simultaneous Localization and Mapping (SLAM) technology, which is mainly used in robotics [15]. Wang et al. (2017) proposed a camera tracking system to tackle the markerless tracking problem using the LINE-MOD algorithm [16].

2.2. Application to construction management

XR technologies have been used primarily in the construction industry to communicate among project participants and identify or understand design elements. Chalhoub and Ayer (2018) conducted a quasi-experiment to explore the influence on the productivity and quality of electrical conduit construction. The results indicated that MR had positive effects: 1) higher productivity, 2) less time to understand the design, 3) fewer errors during the assembly process [17]. Carrasco et al. (2021) assessed the effectiveness of design review using MR versus traditional 2D methods. They found that MR-based design review can effectively communicate 85% of the information to the client versus 70% provided by 2D media [18]. Dai et al. (2021) assessed the feasibility of applying MR to enhancing safety risk communication on construction sites, and they found the potential of MR for visualization, communication, and remote collaboration of safety management on construction sites [19].

MR technologies can be applied effectively in the construction field, and numerous studies have demonstrated their potential. What should be pre-determined is positioning the virtual object in the correct location. On the other hand, it is necessary to move virtual objects in real-time for more effective communication, and there have been few studies on this topic. The spatial alignment method that we propose in this study is a haptic interface for positioning the virtual objects, which is different from the existing method in that users move virtual objects in real-time in a mixed reality environment.

3. SYSTEM DEVELOPMENT

3.1. System components

The haptic interface system developed in this study consists of hardware and software. The hardware is Microsoft's Holorens 2, and the software is a mobile app built using Unity 3D as shown in Fig. 1.

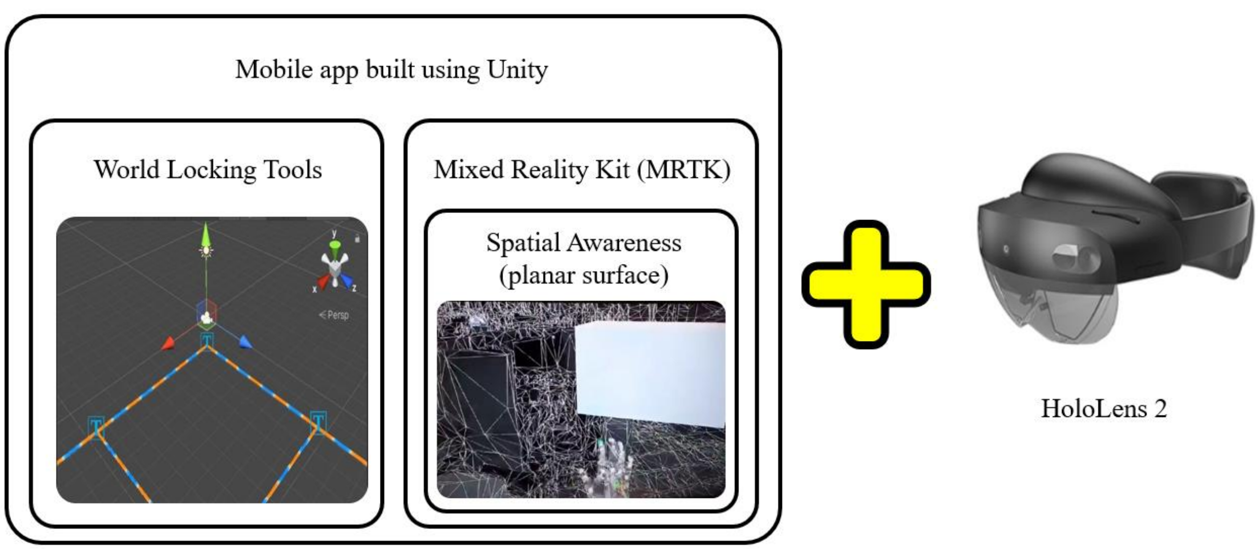
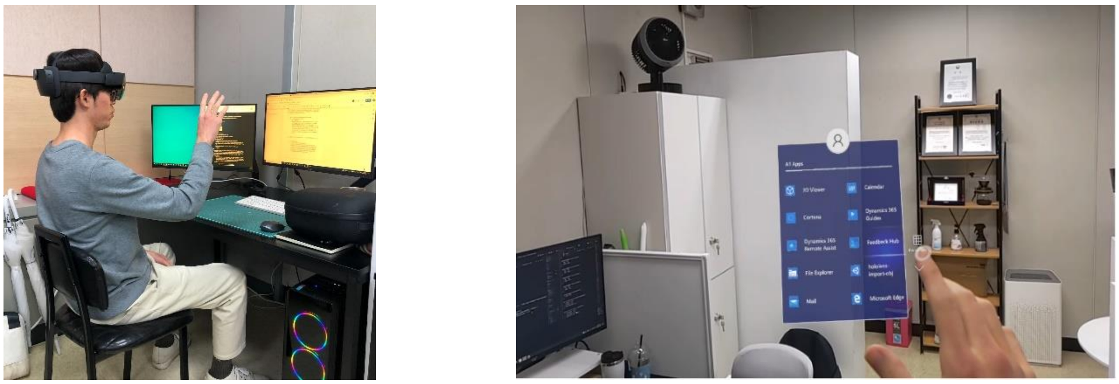


Figure 1. System Components

3.1.1. Hardware - HMD (HoloLens 2)

In this study, HoloLens 2 was employed to implement the haptic interface. HoloLens 2 is a mixed reality-based head-mounted display (HMD) developed and manufactured by Microsoft. The HoloLens 2, which is equipped with a camera, can recognize the environment around the user, and the user can view the real world overlaid with virtual objects as shown in Fig. 2. The user can manipulate the virtual objects in a hands-free manner. HoloLens 2 is widely used because it is comfortable to wear, easy to use, provides sufficient computing power.



a) A user wearing a HMD b) Real world overlaid with a virtual object

Figure 2. Head-mounted display

3.1.2. Software - mobile application

The spatial alignment application operated on HoloLens 2 was developed using Unity, a cross-platform game engine used to create three-dimensional games and interactive simulations. The engine has been widely adopted by many industries, including video gaming, film, automotive, architecture, engineering, and construction.

Mixed Reality Toolkit (MRTK)-Unity is a Microsoft-driven project that provides a set of components of features used to accelerate cross-platform MR application development in Unity. The Spatial Awareness System, one of the components provided by MRTK, overlays mesh data on the surface viewed on the screen of the HMDs. Once the mesh data overlay the surface, the coordinate information of the surface location can be identified. In order to place a virtual object to any location in mixed reality, virtual object vertex coordinates and point coordinate information on the mesh where the virtual object is to be located.

World Locking Tools (WLTs) are used to reduce the location error of virtual objects. When the user changes his/her position, WLTs make spatial anchors with absolute coordinates information at regular intervals. So, the virtual object is located in the original position even though the user changes his/her position. When the user moves after creating the virtual object, the relative coordinates of the virtual object continue to change, and the coordinate information of the spatial anchor is used to reduce the error due to the change in the relative coordinates of the virtual object.

4. SYSTEM OPERATION

The developed haptic interface system operates as follows. This system requires the user to define two sets of segments. The first segment that the user selects is to identify a virtual object to be moved (i.e., segment AB in Fig. 3). Then, the user defines another segment, for instance, segment A’B’ in Fig. 3, on any surface mesh where the user wants the virtual object to be placed.

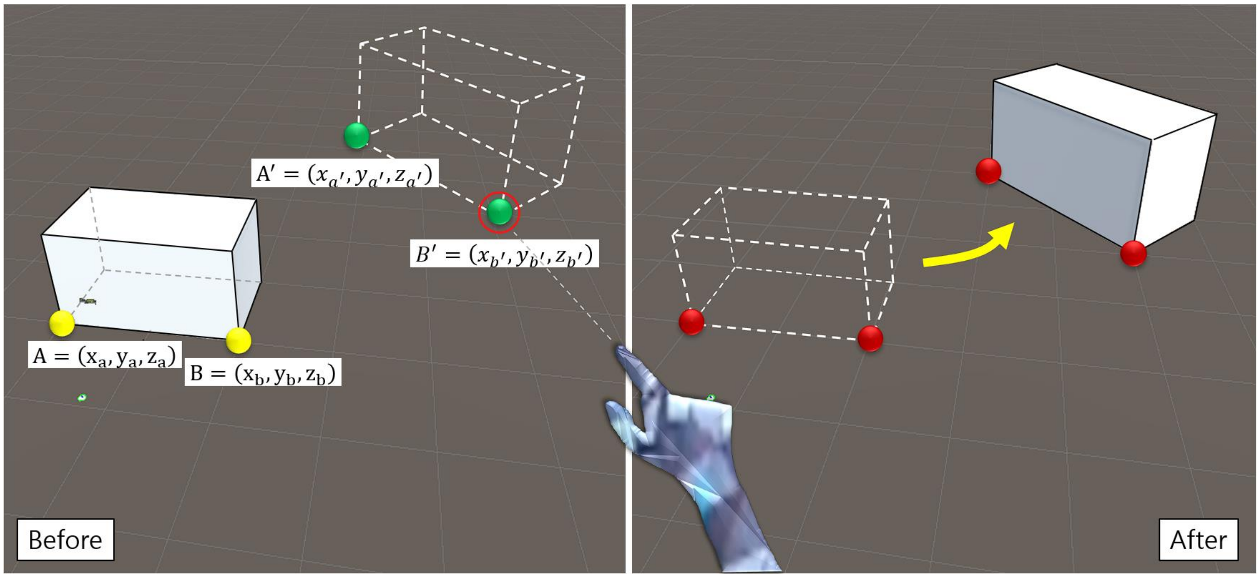


Figure 3. Interacting with a virtual object

1. Define two sets of segments AB and $A'B'$

↓

2. Compute the lengths of AB and $A'B'$’ - (Eq. 1)

↓

3. Compute unit vectors of AB and $A'B'$ - (Eq. 2)

↓

4. Compute rotation angle about y axis – (Eq. 3)

↓

5. Compute scale factor – (Eq. 4)

Figure 4. Process of computing parameters for moving a virtual object

Fig. 4 shows how the developed system works when a user moves a virtual object from location A to location A'. Segment AB is one of the segments of the virtual object, for instance, a segment of the front bottom surface. Segment A'B' is a new location for the virtual object. Given A, B, A', and B' coordinates $A = (x_a, y_a, z_a)$, $B = (x_b, y_b, z_b)$, $A' = (x_{a'}, y_{a'}, z_{a'})$, and $B' = (x_{b'}, y_{b'}, z_{b'})$, we can compute the lengths and unit vectors of segments AB and A'B' (Eq. 1 and Eq. 2). Also, the scale factor and rotation angle about the y axis between segment AB and segment A'B' can be calculated (Eq. 3 and Eq. 4).

$$\overline{AB} = \sqrt{(x_b - x_a)^2 + (y_b - y_a)^2 + (z_b - z_a)^2}, \quad \overline{A'B'} = \sqrt{(x_{b'} - x_{a'})^2 + (y_{b'} - y_{a'})^2 + (z_{b'} - z_{a'})^2} \quad (1)$$

where $\overline{AB}$ = the length of segment AB; $\overline{A'B'}$= the length of segment A'B'.

Two unit vectors are obtained by Eq. 2. One is a vector in the same direction as $\overline{AB}$, and the other is in the same direction as $\overline{A'B'}$. These vectors are later used to calculate the rotation angle of the virtual object about y axis.

$$\boldsymbol{v_{AB}} = \left(\frac{(x_b - x_a)}{\overline{AB}}, \frac{(y_b - y_a)}{\overline{AB}}, \frac{(z_b - z_a)}{\overline{AB}}\right), \boldsymbol{v_{A'B'}} = \left(\frac{(x_{b'} - x_{a'})}{\overline{A'B'}}, \frac{(y_{b'} - y_{a'})}{\overline{A'B'}}, \frac{(z_{b'} - z_{a'})}{\overline{A'B'}}\right) \quad (2)$$

where $\boldsymbol{v_{AB}}$ = unit vector of segment AB; $\boldsymbol{v_{A'B'}}$ = unit vector of segment A'B'.

Given unit vectors of the two segments, the rotation angle θ_r between two vectors is

$$\theta_r = cos^{-1}\left(\frac{v_{AB} \cdot v_{A'B'}}{\|v_{AB}\|\|v_{A'B'}\|}\right) \quad (3)$$

The scale factor used to change the size of a virtual object without changing its shape is obtained by Eq. 4.

$$S.F. = \frac{\overline{A'B'}}{\overline{AB}} \quad (4)$$

As the first step in interacting with virtual objects in mixed reality, we challenged moving a cuboid to the desired location using finger-pointing. This study defined two segments to compute the scale factor and rotation angle of the virtual object to be moved. As a result of testing a cuboid, the user can successfully move it to the desired location.

One can use Hololens 2 to move and resize objects. Hololens 2 is just hardware with sensors and mixed reality scenarios such as tracking, mapping, and registration of virtual objects. Registering a virtual object in the real environment involves several processes:

1. Tracking the location of the virtual object
2. Mapping to recognize the real environment
3. Registration of the recognized object to the correct location in the real environment.

Hololens 2 is used as a controller that can access and manipulate MR scenarios using its sensors. What actions we perform using Hololens 2 can vary with the customized combination of functions in the Mixed Reality Toolkit. Hololens 2 moves objects in dimensionless virtual space to approximate positions. However, the system developed in this study enables the object to be moved to an accurate position. Since this system recognizes the surfaces through the Spatial Awareness System, it can accurately move the object to the desired position.

5. CONCLUSION

This study presented a haptic interface system in MR that enables users to interact with virtual objects such as BIM elements. If multiple stakeholders can share the screen of the user moving the BIM object, it will be beneficial for communication. Especially, it will be advantageous for communication between on-site workers and office managers. The system to share the screen with other users will be carried out in the further study. On the other hand, if the object is moved from the virtual, its location information may be updated in BIM. Though the current system does not provide that feature, it will be beneficial for creating as-built drawings if it does.

The interface system consists of an MR-based HMD and a mobile application developed using Unity 3D. The users wear an HMD and interact with BIM objects using their hands. The developed interface's applicability was verified by testing a virtual object, a cuboid. Using this system, the users can conveniently manipulate BIM elements in the construction site. Practically, this system can help BIM designers or site workers. Especially, this system can be of great help to workers who create as-built drawings. Also, sharing what the site worker sees through the HMD with other stakeholders will greatly help communications management.

The limitations of this study are as follows. First, The accuracy performance of the developed system needs to be evaluated and analyzed compared to the existing method. Until recently, marker-based methods have been mainly used in the spatial alignment of virtual objects. The method presented in this paper should be better in terms of convenience in manipulating the BIM objects; however, it is necessary to evaluate whether the accuracy is superior to the existing method. Second, the developed interface only works for the cuboid. Future studies should be expanded to work for objects of all shapes. Third, this study dealt with the object's rotation only about the y axis under the assumption that BIM objects are horizontal to the ground. However, a more robust system can be developed when rotation about the x-axis and z-axis is possible. Finally, the BIM does not change in this study. This study was conducted only on cuboid object.

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