

Visualization Research Center (VISUS)

Master Thesis

Paper-based Tangible User Interface as Interaction in Mixed Reality

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Abstract

In wearable mixed reality systems, hand interaction has several drawbacks of interact with virtual objects. In the thesis, we proposed the Paper Cube-based Tangible Interface (PCTI) which gave users an alternative to interact with a virtual object using a cheap and readily available tangible prop. We presented four different potential prototypes, and ultimately implemented the one that better met our requirements. During the implementation process, the image tracking technique that we employed in the interface could not let the interface achieve the expected performance. Therefore, we replaced it with optical tracking technology to improve the tracking accuracy. A comparative study was conducted to evaluate PCTI and hand interaction in HoloLens 2. The results revealed that PCTI on object manipulation was as efficient as hand interaction and provided a better user experience. Its usability performance was rated as good. Finally, we presented the current limitations of PCTI and had some suggestions for further improvement.

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Acronyms

AR Augmented Reality. 19

HCI Human-Computer Interaction. 14

HMD Head Mounted Display. 13

MR Mixed Reality. 13

NASA-TLX NASA Task Load Index. 34

PCTI Paper Cube-based Tangible Interface. 14

SUS System Usability Scale. 34

TI Tangible Interface. 14

TUI Tangible User Interface. 14

UX User Experience. 27

1 Introduction

Mixed Reality (MR) is an evolving technology that blends the virtual world with real world. To be more precise, MR contains three main features: (1) combines physical objects with virtual objects concurrently; (2) interacts in real-time; (3) maps physical objects and virtual objects spatially [HMS+15]. These features enable to blur the boundary between both environments and increase the diversity of interaction for various purposes in different fields, such as medical, education, tourism, architecture [AKG19; DIM+18; HFS+19].

1.1 Interaction Methods

For MR Head Mounted Display (HMD), the hand gesture is considered an intuitive interaction to manipulate the virtual object. Take Microsoft HoloLens 2 as an example, it creates a hand ray that is emitted from the palm as an extension of the hand, and there is a cursor attached to the end of the ray. By pinching the index finger and thumb together, the target object which intersects with the cursor would receive the command from the gesture (see Figure 1.1a). If a cube, also called bounding box, is shown around the virtual object, then it represents that the object can be manipulated (see Figure 1.1b). When the cursor is landed on the bounding box, the whole object can be moved; on the rotate handles that appear on the edges, the object can be rotated; on the resize handles that appear on the corners, the object can be resized (see Figure 1.2).

However, several disadvantages are associated with this interaction. A drawback is the limitation of object rotation. Generally, there are two approaches to rotating an object, using the rotate handles or rotating the wrist while moving the object. These approaches cause the object can only be rotated on one axis at once or to be restricted to the wrist range of motion. Besides, taking aim and grabbing

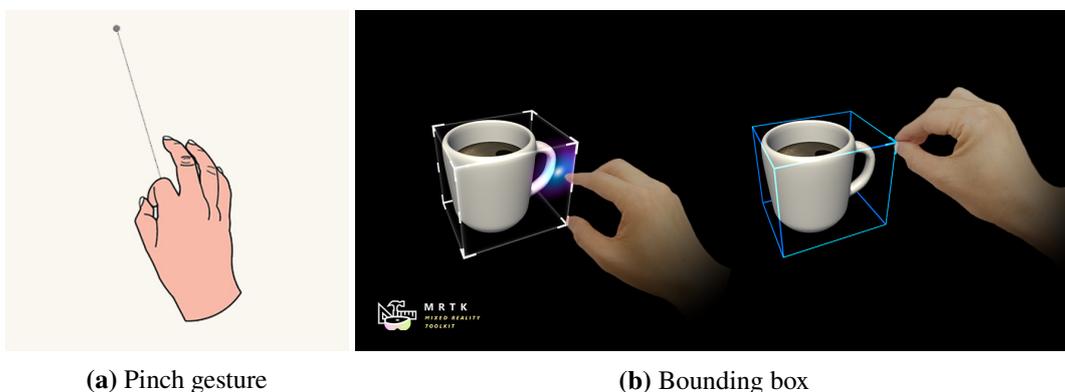


Figure 1.1: Hand interaction on HoloLens 2 [Doca; Docb]

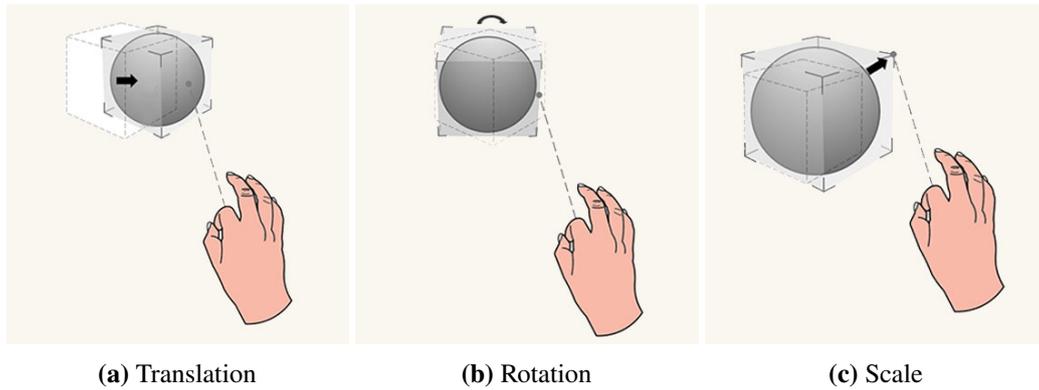


Figure 1.2: Object manipulation by hand interaction on HoloLens 2 [Docb]

an object in a certain circumstance is also a challenge. The tiny-/huge-sized object or long distances increase the difficulty of object manipulation. The small inaccuracy in the distance between the cursor and the object can have a large effect on grabbing the object.

The use of Tangible User Interface (TUI) is widely spread and offers interactive couplings of physical objects with digital information. In immersive technology, it refers to (1) virtual objects are matched with physical objects; (2) users interact with virtual objects by manipulating the corresponding physical objects [BKP08]. This interface significantly enriches the various forms of interaction in Human-Computer Interaction (HCI) [HSU04]. Obviously, the core concept of TUI aligns with MR, which is moving digital information from the virtual world into the real world to augment users' reality. In early previous research, it is certificated that TUI is superior to the gesture interaction in the user experience of MR [BB21].

Even so, there are some limitations to be considered to apply TUI in MR. Tangible Interface (TI) typically involves electronic sensors or devices, which are expensive and challenging. Additionally, the weight of TUI influences its scalability. The heavy TUI in dynamic scenario requires users to make more efforts to manipulate it, and this leads to a degrading user experience [BB21].

1.2 Motivation

Given the issues above, we intend to create a TUI with a low-cost, lightweight tangible prop to make up for the shortcomings of hand interaction and refine object manipulation in wearable MR system. The interface developed and introduced in the thesis is called Paper Cube-based Tangible Interface (PCTI). It can achieve the basic manipulation of virtual objects in MR: translating, rotating, and scaling. We design a user study to compare the PCTI with hand interaction in Microsoft HoloLens 2. In the assessment, we measure the operating efficiency, workload, and usability of these two interactions. Our contribution is summarized as follows: (1) the design of PCTI for MR; and (2) the comparison and assessment between PCTI and hand interaction.

The thesis is organized as follows. In Chapter 2, we explore and summarize some previous research about TUI and interaction in MR. Then Chapter 3 brings out the important concept of our study, explains the workflow of the interface, and introduces the design of preliminary prototypes. Chapter 4 describes the detail of implementation, the challenges we faced during implementation,

and the alternative to solve the problems. In Chapter 5, there is a user study to evaluate the performance of the system. Finally, we reach some conclusions and provide several insights for future work in Chapter 6.

2 Related Work

In this chapter, we will discuss some related work that influenced the decision-making for the concept and the implementation of the paper-based cube system.

2.1 Tangible User Interface in Immersive Head-Mounted Displays

Numerous research of TUI in the immersive environment has been conducted for several decades. Ohshima et al. [OKYT03] proposed two different configurations of TUI that could be introduced to MR HMD. One of the configurations is to consider TUI as an intermediary between the user and controlled objects. The user interacts with the TI which controls the virtual objects to control the virtual object indirectly (see Figure 2.1a). Kawashima et al. [KIK+01] explored the virtual object scene assembly with the TI and proposed the Magic Paddle system to support it. The user could use the paddle to copy any virtual furniture from a book and then transfer the virtual furniture to a virtual room. By picking up and dropping the virtual furniture into the virtual scene, the user could simulate the layout of the room.

The other configuration is registering the TI and the observed virtual object in the same space. In other words, they are identified as one object (see Figure 2.1b). This TUI configuration reduces the sense of distance to the surrounding virtual objects and becomes more direct than when only the visual sense is available [OKYT03]. Ohshima et al. [OKYT03] implemented this idea to the automobile interior design. When the user sat in the real driver's seat with a HMD, virtual images of automobile interior design were superimposed onto the skeletal frame model of the dashboard in front of the user. Song et al. [SZS+19] developed a mixed reality storytelling system that used handicrafts as a TI. The virtual models were placed on the handicrafts which were used to create and tell stories by the user. To decrease the mismatch of TUI between visual and haptic, Hettiarachchi and Wigdor [HW16] designed an Annexing Reality system. The system scanned the physical

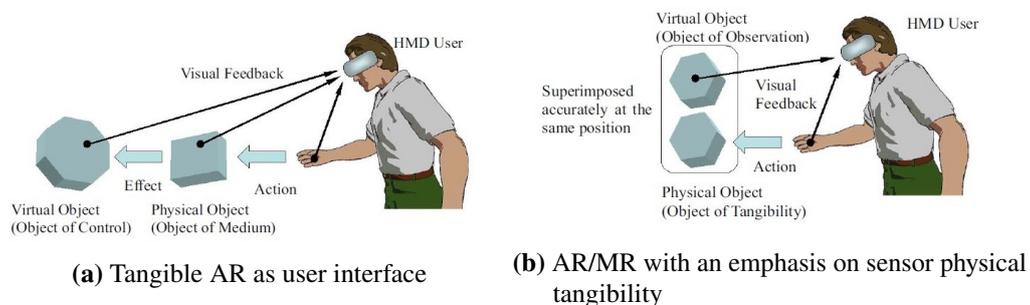


Figure 2.1: Tangible interface in AR/MR [OKYT03].

objects around the user and picked the physical objects which matched the visual models based on their physical characteristics. Then, overlay the visual models on the selected physical objects to provide better haptic experiences for virtual objects.

These configurations could also be combined to provide more kinds of interactions and a larger design space. Satriadi et al. [SSE+22] proposed a conceptual approach that used a tangible globe to achieve geospatial data visualization. The visual data could be visualized above the surface of the tangible globe to create a geographic idiom or around the tangible globe to display diagrams. Alternatively, overlaying the appearance of a planetary on the surface of the tangible globe for globe designing.

2.2 Paper as Tangible Interface

Paper materials are quite common mediums for TUI. Based on its strengths of lightweight and shape-changing, it is suitable to combine with various components to build a low-cost TI. Fiducial markers are often employed to identify and report the position and orientation of the paper-based objects to support tangible interaction [JGAK07]. Kelly et al. [KSHB18] created an ARcadia toolkit that allowed novices to customize a real-time and interactive TUI prototype rapidly. ARcadia enabled to implement tangible interaction with built-in support for common interface elements, like buttons and sliders, and event-based control of system behavior. One example was mapping music operations to different shapes of cardboard with fiducial markers. After the real-time webcam identified the fiducial markers, the system executed the corresponding behaviors to play the music or control the music effects. Zheng et al. [ZGD20] explored paper's physical affordance, such as cutting, folding, bending, and gluing, while using these characteristics to conceal and reveal fiducial markers. They presented diverse paper structures to construct and deconstruct the fiducial markers. For example, constructing markers with paper edges, paper buttons, or stretchable paper structures.

Fiducial markers are not the only method to track physical props. Becker et al. [BKMS19] developed a system that allowed the user to assemble arbitrary shapes of paper snippets with any suitable surface to create a personalized user interface. Each paper shape was added an interaction functionality. The system employed the RGBD camera above the interaction space to accomplish the markerless tracking of the user's fingers and the paper shapes on a surface. The interaction functionality was triggered by the manipulations of the shapes, such as moving distances of the shapes or the duration of tapping shapes.

In addition to passive tangible interaction, paper can also be used to demonstrate active tangible interaction. Actively responding from tangible props to users' operations can greatly enhance the user experience of the system [AY12]. Amano and Yamamoto [AY12] utilized the actuation capability for paper sheets of electrostatic actuators to realize the interaction between animated computer graphics with plain paper sheets. Transparent planar electrostatic actuators were placed on the surface of a flat-panel display which displayed the computer graphics and the location of the paper sheet positioned above was detected by a camera. Once a collision occurred between the paper sheet and the computer graphics, electrostatic actuators would push the paper sheet to move in an appropriate direction.

2.3 Tangible Interface for Object Manipulation

When talking about using TUI to manipulate objects in Augmented Reality (AR), there are three kinds of physical prop design that are often employed: cup, paddle, and cube. Ha and Woo [HW10] conducted an evaluation of these physical prop designs in order to compare their stability, speed, comfort, and understanding in 3D object selection, translation, and rotation on a 2D plane.

Picking and dropping gestures are common gestures to interact with a cup-shaped prop (see Figure 2.2a). A fiducial marker is attached to the top of the cup. It provides more comfort in object translation and its manipulation is easy to understand. However, sometimes the tracking can be unstable when picking up, dropping, and tilting the 3D object due to the angle of the fiducial marker suddenly changing [HW10]. Kato et al. [KTT+03] presented a city-planning system that used a cup-shaped prop to arrange the layout of 3D objects, like trees or buildings. The interaction included picking, dropping, moving, and deleting the object.

In paddle manipulation, the user grasps the paddle-based prop on the hand and uses the picking and tilting gesture to select and manipulate the 3D object (see Figure 2.2b). If the paddle is very close to a 3D object, the object will be placed on the paddle and can be manipulated until using the tilting gesture to drop the object. It also exists a tracking instability issue but compared to the cup-shaped prop, the marker on the paddle can be recognized easier. The manipulation of the paddle is intuitive and easy to use [HW10]. This manipulation had been applied to simulate room decoration in AR [KIK+01].

In cube manipulation, there is a virtual line in the front of the cube which is used to select and drop the 3D object (see Figure 2.2c). Once the line tip has a collision with an object for a specific period of time, the object will be selected. If the marker is hidden by the hand, the selected object will be released. Since the user needs to grasp the cube when manipulating, marker occlusion by hand occurs frequently. This manipulation is not suitable to manipulate small 3D objects, and continually holding the hands in the air causes fatigue [HW10]. Lee et al. [LNBK04] used the cube-based prop as a controller to select and manipulate the 3D object.

The configuration of TUI we have mentioned above are similar to Figure 2.1a, but it is still possible to execute the object manipulation when the virtual is registered to the physical prop (see Figure 2.1b). Bozgeyikli and Bozgeyikli [BB21] designed a tangible cube with a virtual projection from MR HMD on it. The cube adopted both controller and image tracking to achieve accurate tracking, and its manipulation was similar to the way the cube was manipulated in real life. In the study, they compared the tangible cube with controller interaction and hand gesture interaction on object translation and rotation. According to the results of the study, TUI and controller interaction performed better than hand gesture interaction. Hand gesture interaction took more time to achieve

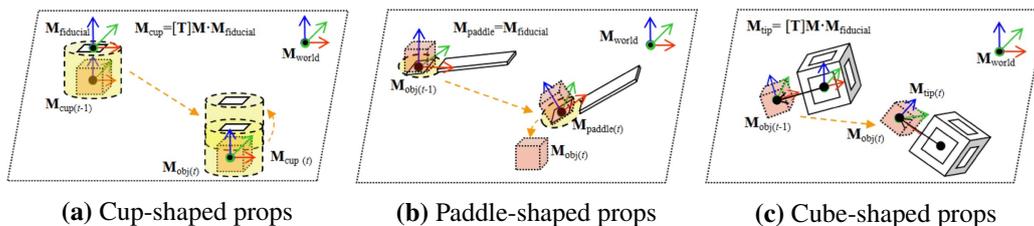


Figure 2.2: 3D object manipulation in a tangible augmented reality environment [HW10].

either object translation or object rotation. If the tangible prop had a similar form to the virtual object, the user experience enhanced. However, the weight of the cube asked the user to take more effort to hold it. Even combining both controller and image tracking for cube tracking, minor inaccuracies still existed.

2.4 Distinction to the Thesis

To realize the object manipulation without distance limitation, it is ideal that the TUI is used as an intermediary between the user and the controlled object instead of registering together with the virtual object. Compared to the work made by Bozgeyikli and Bozgeyikli [BB21], we are more focused on developing a low-cost, flexible, and lightweight TUI. In the study, we only evaluated the performance and usability of PCTI and hand interaction. In addition to translation and rotation, scaling is included as a comparative item as well.

Considering that our working space is in a 3D environment rather than on a 2D plane, the construction and deconstruction of the fiducial markers on physical prop are more complicated than on flat paper (see Section 2.2). We got several inspirations from the research of Zheng et al. [ZGD20]. In comparison with the cube-based prop in Ha and Woo [HW10] and Lee et al. [LNBK04], we abandoned the virtual line in the front of the cube as object selection is not discussed in this thesis.

3 Design

This section points out our core concept of PCTI. Based on this concept, we illustrate the entire workflow of this system and propose four preliminary prototypes of the tangible prop.

3.1 Concept

The goal of this thesis is to propose a flexible and inexpensive interaction technique that can address the limitations of object manipulation in hand interaction in an immersive environment. Object manipulation mainly refers to moving, rotating, and resizing objects. With a tangible prop in our hands, any interaction between the users and the prop is mapped to the virtual object in MR to achieve the effect of control.

To achieve the goal, we first proposed several preliminary prototypes of the tangible prop. We compared the performance and usability between them and picked the one which fitted our requirements better as the final prototype. After implementing and improving the PCTI system, we designed a user study to evaluate the performance of the system.

3.2 System Workflow

The workflow of PCTI is shown in Figure 3.1. The system is installed on the HoloLens 2 and is used with a cube set. In accordance with the design of prototypes, there are one or two cubes in the cube set. Each cube is assigned different properties to manipulate virtual objects, such as moving, rotating, and resizing the objects.

After the users wear the HoloLens 2 and start up the PCTI, the camera would be turned on and automatically detect the position of the paper-based cube. As soon as the cube is detected, its current position would be tracked and recorded. With cube tracking, the system compares the position of the cube at different frames and calculates the movement quantities. Property of cube, combined with movement quantities, the virtual object in HoloLens 2 is directly manipulated with a one-to-one mapping of the cube.

In every frame, the system would check whether the paper-based cube is still captured by the camera. Once the cube is out of the sight of the camera, it would be determined as losing tracking and deprived functionality of object manipulation until it is re-detected by the camera again.

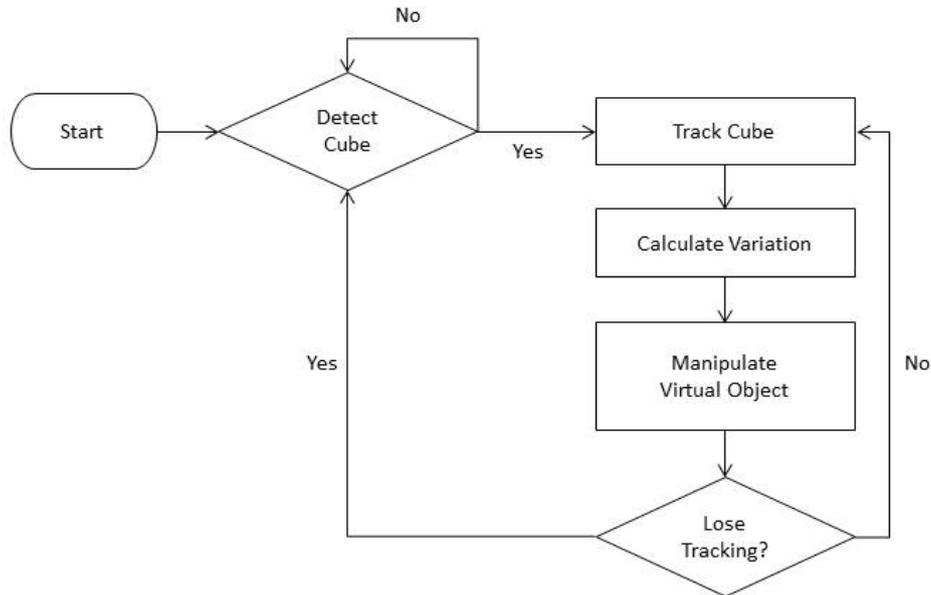


Figure 3.1: Workflow diagram of PCTI.

3.3 Prototype Design

In the early stage of prototype design, we came up with two key principles which were followed by all prototypes. First of all, the material of the tangible props is paper or other paper-based products, such as paperboard and cardboard. Paper materials have the advantages of low cost, lightweight, accessibility, and formability. Considering our goal, paper materials are very suitable as the material for tangible props. Secondly, the appearance design of tangible props should be a solid geometric model in a simple form. The simple form can reduce the influence of form complexity on the results and also diminish operating difficulty to avoid user confusion. Therefore, the cubic shape becomes our first choice.

The following prototypes are developed based on these two principles: Twin Cube prototype, Push-and-Pull Cube prototype, Infinity Cube prototype, and Boob Cube prototype. The structure of each prototype looks similar in physical appearance. All of them include a primary paper-based cube which is used to move and rotate the virtual object. The main differences are the operation of resizing objects and switching modes.

3.3.1 Twin Cube

The Twin Cube prototype is consist of two paper-based cubes, a primary cube and an auxiliary cube. Both of their six faces are respectively covered by image markers which are used for detection and tracking. Since every face is attached to a unique image marker, HoloLens 2 can scan those markers to recognize the cube and its corresponding functionality.

The primary cube is responsible for translation and rotation (Figure 3.2a). When the primary cube is detected by HoloLens 2, the virtual object would enter Move Mode, that is, changing the current position and rotation angle of the virtual object. Any movement that happens to the cube would reflect on the virtual object directly. In other words, its motion is synchronized with the motion of the virtual object. For example, if the cube moves forward to the north, the users can see the virtual object move forward to the north as well. To scale the virtual object, both primary cube and auxiliary cube must be detected simultaneously so that the virtual object can get into Scale Mode. Under Scale Mode, the change in distance between two cubes controls the size of the virtual object. If two cubes are kept close to each other, the volume of the virtual object reduces. Conversely, pulling away distance enlarges the volume (Figure 3.2b). To stop the object manipulation, the only method is losing track of the cubes. Putting one's hand over the cubes would interrupt cube tracking and let virtual object break away from Move/Scale Mode.

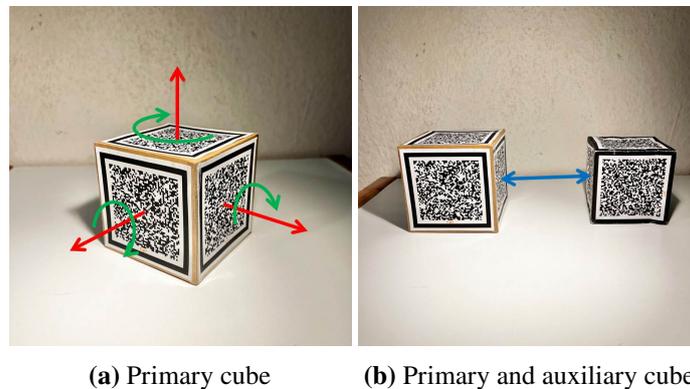


Figure 3.2: Twin Cube prototype comprises a primary cube and an auxiliary cube. By moving (red arrows) and rotating (green arrows) the primary cube, the virtual object would move and rotate in the same way synchronously. By adjusting the distance between primary cube and auxiliary cube (blue arrow), the size of the virtual object would be changed.

3.3.2 Push-and-Pull Cube

Push-and-Pull Cube prototype is a variant of Twin Cube prototype. The prototype also contains a primary cube and an auxiliary cube which are covered by image markers. However, to increase the flexibility of interaction, we adopt a novel construction to build the primary cube. The primary cube is split in half, and the two halves are connected with two paper strips. Detaching one half of the cube from the other half impacts marker detection and lead to losing track of the cube. Compared to blocking the image markers by hand, this way is easier and more intuitive. Except for this part, users interact with the cubes to manipulate the virtual object in the same way as they do in Twin Cube prototype (Figure 3.3).

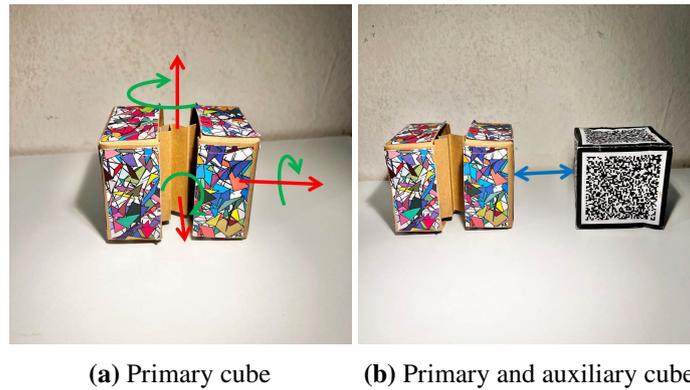


Figure 3.3: Push-and-Pull Cube prototype comprises a primary cube and an auxiliary cube. By moving (red arrows) and rotating (green arrows) the primary cube, the virtual object would move and rotate in the same way synchronously. By adjusting the distance between primary cube and auxiliary cube (blue arrow), the size of the virtual object would be changed.

3.3.3 Infinity Cube

The Infinity Cube prototype is inspired by infinity cube, a $2 \times 2 \times 2$ cube that can be opened and put back together from different directions. It combines primary cube and auxiliary cube, which are used in Twin Cube prototype and Push-and-Pull Cube prototype, to form a single tangible prop. By folding repeatedly, the switch between Move Mode and Scale Mode can be accomplished in a single cube (Figure 3.4b).

When the cube is shown as Figure 3.4a, six faces of the cube are covered with image markers, then the virtual object is in Move Mode. Likewise, any movement of the cube would map to the virtual object directly. In contrast to two previous prototypes, we only use one image marker to represent Scale Mode (Figure 3.4c). To resize the virtual object, the side of the marker needs to

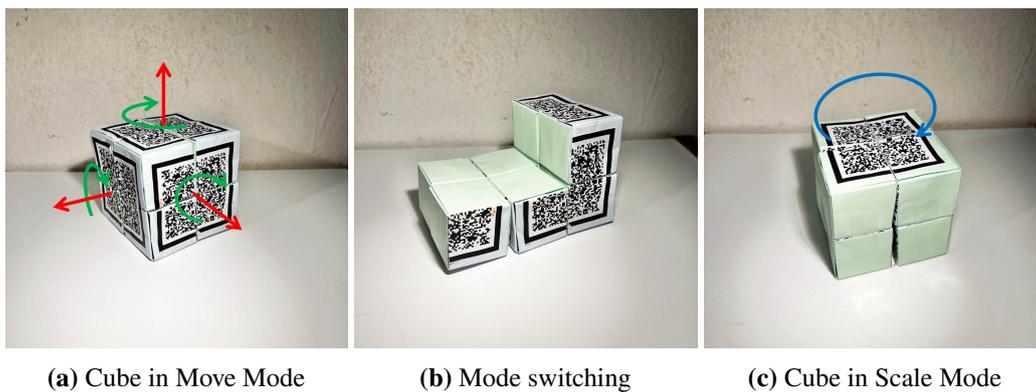


Figure 3.4: Infinity Cube prototype. By moving (red arrows) and rotating (green arrows) the cube in Move Mode, the virtual object move and rotate in the same way synchronously. By rotating the cube in Scale Mode (blue arrow), the size of the virtual object can be changed.

face up and rotate horizontally. Clockwise rotation allows to shrink virtual object. Conversely, Counterclockwise rotation makes the virtual object become bigger. Moreover, losing track of the cube can be achieved by folding the cube into different shapes to destroy the completeness of image markers.

3.3.4 Boob Cube

The boob cube is a $1 \times 1 \times 2$ cube, that is fully rotatable on a single axis of rotation. The Boob Cube prototype uses this kind of cube as a tangible prop. A single cube is divided into two halves. To let halves of the cube stay together, a round head fastener is placed on the center point as a rotating axis. Like Infinity Cube prototype, a single cube is plastered with image markers and contains both Move Mode and Scale Mode. The main difference is the pattern of the image marker which is used for Scale Mode. In Infinity Cube prototype, the image marker for Scale Mode is totally unique and there is no repetition with the image markers for Move Mode. However, in Boob Cube prototype, it originates from segmenting and reassembling the image markers for Move Mode. Since the appearance of the cube looks similar in different modes, we leave some marks on one face of the cube. If marks appear on the same face, that is, the interaction is on Scale Mode. In contrast, if they are on opposite sides of the cube, then the interaction is on Move Mode.

The operation of moving and rotating virtual object is the same as the operation in previous prototypes (Figure 3.5a). To resize the virtual object depends on the vertical movement of the cube (Figure 3.5c). Moving up increases the volume of the virtual object, and moving down decreases the volume of the virtual object.

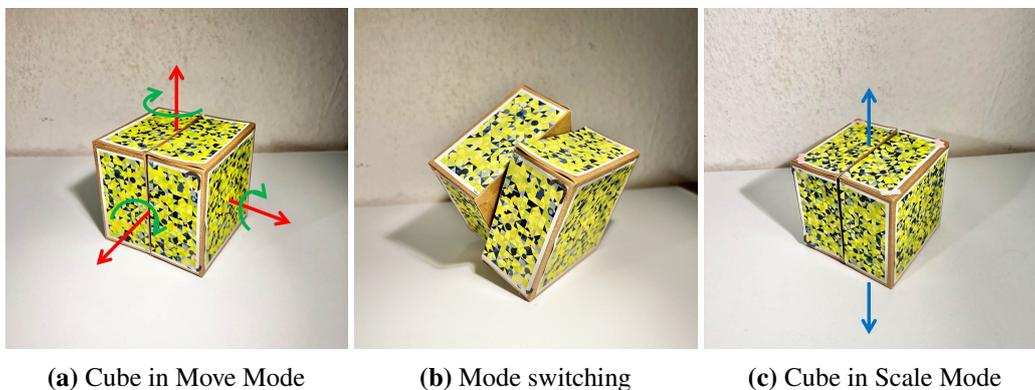


Figure 3.5: Boob Cube prototype. By moving (red arrows) and rotating (green arrows) the cube in Move Mode, the virtual object would move and rotate in the same way synchronously. By moving the cube in Scale Mode up and down (blue arrow), the size of the virtual object would be changed.

3.3.5 Decision

After thorough analysis and discussion, we decided to adopt the Boob Cube prototype as our final prototype. In comparison with Twin Cube and Push-and-Pull Cube, Boob Cube integrates all functionalities together in a single cube so that it is less constrained by two-handed operation. Users

3 Design

can operate the Boob Cube with either one hand or both hands in any mode, but they must use both hands to operate Twin Cube or Push-and-Pull Cube to resize the virtual object. From the viewpoint of operation difficulty, Boob Cube takes less effort to switch the modes. Minor rotation to half of the cube can stop the tracking of the cube and interrupt object manipulation. Based on these considerations, the Boob Cube is an appropriate TI for further development.

4 Implementation

After firming up the core concept and details of the interface, we got started with the implementation part. In the process of testing, we found that a performance issue in the interface existed and the result was not as expected. Nonetheless, we overturned the previous design and came up with a new alternative which greatly improved the performance issue. In this chapter, we explain all the steps of development, including technical details, performance issues, and solutions.

4.1 Implementation Details

PCTI is implemented by using Unity version 2020.3.3f1¹ with Microsoft Visual Studio 2019². The MR HMD we choose as an experimental device is Microsoft HoloLens 2³. The implementation of PCTI and evaluation between two interactions take place in the device. Microsoft Mixed Reality Toolkit⁴ is a collection of packages that is used to realize the development of cross-platform MR application in Unity. It offers a variety of User Experience (UX) components to build mixed reality experiences.

For detecting and tracking image markers, we use Vuforia SDK version 10⁵ to do the tracking. This technique can track the positions of single image markers (Image Targets), or track the position of multiple image markers and arrange them into regular geometric shapes (Multi Targets), such as cubes. As for image markers, they are printed in size 7×7 cm in order to have a better tracking effect.

4.2 Interaction Logic

The Boob Cube is seen as an active game object in Unity as soon as it is detected as Move Mode or Scale Mode by Vuforia AR Camera. In every frame, Unity saves the transform data of the cube to record its current position, rotation, and scale. When the cube is detected as Move Mode, in order to translate the virtual object, first the system calculates the relative movement between the current position and the previous position of the cube. The relative movement multiplies by the desired speed, then it is added to the position of the virtual object. In the same way, the rotation of the virtual object depends on the relative orientation between the current rotation and the previous rotation of the cube. If the cube is detected as Scale Mode, the system only calculates the relative

¹<https://unity3d.com/unity/whats-new/2020.3.3>

²<https://docs.microsoft.com/en-us/visualstudio/releases/2019/release-notes>

³<https://www.microsoft.com/en-us/hololens>

⁴<https://docs.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2/?view=mrtkunity-2022-05>

⁵<https://library.vuforia.com/>

movement of the cube on the y-axis. The relative movement is converted proportionally to a scaling value and added to the scale of the virtual object. The calculation would continue until the Boob Cube is detected neither as Move Mode nor Scale Mode, that is, Vuforia AR Camera loses track of the cube.

4.3 Challenges

While testing the PCTI, we found that there were several challenges to object manipulation by using the tangible prop. These challenges made it difficult for Vuforia AR Camera to recognize images and resulted in losing track of the cube. Based on this situation, we discussed and proposed several factors that might enhance the chance of losing track.

Firstly, once some parts of the cube are out of sight, there is a high probability that the cube would be lost track because of the insufficient recognizable features. It is too difficult to predict the time of occurrence when we use the interface. The best solution is that the whole cube stays within sight of HoloLens 2 so that all the features on the cube can be well detected by the camera. Having said that, this restriction is too tough to achieve for some users, and in some cases, it would cause limitations on object manipulation. For instance, if the virtual object is positioned above or at eye level, the cube should also be held at the same level most of the time. Then the users need to take more effort into it. Raising arms for a long time increases the fatigue of users and reduces willingness to use the interface.

The second factor is lighting conditions. Brightness and contrast play a critical role in detection performance [ZGD20]. Adequate and appropriate light can help the image markers to improve overall contrast and present more usable features to be well visible in the camera view. Despite we were in an indoor environment and had stable lighting conditions, these lighting conditions could not provide enough brightness to every image marker in motion all the time. It may interrupt the tracking of the cube in some cases.

Lastly, the way to hold the cube could also be a problem. The proper way to hold the boob cube is to place the fingertips on the edge pieces of the left and right sides of the cube. Try to avoid wrapping hands around the cube when using it. In this way, the image markers would not be hidden by the fingers. The less the cube is covered by hands, the more features the camera can detect. Nonetheless, the fingertips are not always put on the appropriate places, especially when switching the modes.

4.4 Alternative: Optical Tracking

To address the performance issue of PCTI, we assessed the probability of improving image tracking on Vuforia. Nevertheless, there exists some technical difficulty to do so. We decided to draw our attention from image tracking to optical tracking. OptiTrack Motive⁶ is a software platform to control optical motion capture systems. It can track objects in six degrees of freedom in real-time. Since the position of the cube is captured by multiple synchronized cameras which are arranged

⁶<https://optitrack.com/software/motive/>

around the room, the cube no longer needs to stay within sight of HoloLens 2. Moreover, compared to image tracking, optical tracking provides more precise tracking data with fewer losing track issues.

4.4.1 Markers and Tracking

One of the changes between using image tracking and using optical tracking is markers. Instead of using images pasted on the surface of the cube as markers, optical tracking uses retro-reflective markers which are placed onto the cube. A rigid body in Motive is a collection of attached markers on an object which are interconnected to each other with an assumption that the spatial relationship among the markers remains unchanged. Taking advantage of this feature, we placed six markers asymmetrically on the cube to introduce the asymmetry and avoid the consistency of markers arrangement in two different modes. Then we created two different rigid bodies which recorded the spatial relationships of the markers when the cube was in Move Mode and Scale Mode respectively. If the cube is in Move Mode, the unique spatial relationship of attached markers would be recognized by Motive and activates the corresponding rigid body. Hence, the placement of markers is vital for recognizing which mode the cube is in.

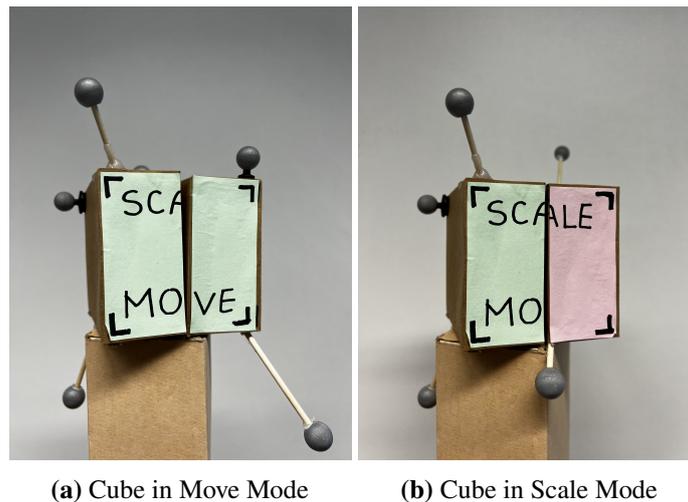


Figure 4.1: Boob Cube prototype in optical tracking. The method of operating the cube is the same as it is in image tracking.

4.4.2 Data Streaming

To stream the data from OptiTrack cameras to HoloLens 2, we built a Unity project as a server that receives the tracking data from Motive and forwards it to HoloLens 2. OptiTrack Unity3D Plugin⁷ is a plugin that allows to stream the real-time data from Motive into Unity. After importing the plugin package to the server, we set up a client prefab object which was responsible for managing the internet connection between Motive and the server. More importantly, it received the tracking

⁷https://v22.wiki.optitrack.com/index.php?title=OptiTrack_Unity_Plugin

data from the connected Motive and made the data available within the scene. Besides, we added two rigid bodies which correspond to the rigid bodies we have already created in Motive. These two rigid bodies would be animated according to the associated rigid body movement in Motive.

As for the data transportation between the server and HoloLens 2, RiptideNetworking⁸ is used to establish connections between Unity projects and send data back and forth. Once the connection succeeds, the HoloLens is forced to receive the data stream from the Motive through the server. The sending and receiving packages are over UDP, so the data is continuously sent to the HoloLens whether it receives the data or not.

4.4.3 Data Processing

As long as the connection from Motive to HoloLens 2 is made, the steady data streams of rigid bodies would send to HoloLens until any one of the connections is dropped. Even though the rigid bodies are lost tracking, Motive would send their last position and rotation data continuously. In this case, the system cannot determine which mode the cube is in right away. Therefore, when HoloLens 2 receives the data stream, it would check the current status of two rigid bodies according to their positions. If the position and rotation data keep showing the same value, then the Motive loses tracking of the rigid body and the corresponding manipulation would not occur.

4.4.4 Triangulation

The most critical part of combining PCTI with the OptiTrack system is coordinate transformations. It is not a problem for Vuforia image tracking because both cube and the virtual objects use the HoloLens coordinate system. The coordinate system of HoloLens 2 is a Cartesian coordinate system and is set up when launching the application for the first time. The position of the headset is set as the origin. The positive X-axis points to the right-hand side of users, the positive Y-axis points up, and the positive Z-axis points away from the users. However, the OptiTrack coordinate system is set as what Figure 4.2 shows. The positive X-axis points to the opposite side of the door, the positive Y-axis points to the ceiling, the positive Z-axis points to the left side of the room, and the origin is the center of the room.

Instead of finding out the transformation matrix between two coordinate systems, we decide to reconfigure the local coordinates of virtual objects in HoloLens coordinate system so that the local coordinate system can overlap perfectly with the OptiTrack coordinate system. First, we prepared a rectangular cardboard which was stuck with four unique image markers on the corners. The cardboard was placed on the center of the room, also the origin of OptiTrack coordinate system, then use HoloLens to scan the markers and record the their world coordinates. The world coordinates of the center of the cardboard can be calculated from triangulation of multiple markers. Finally, set the origin of local coordinate system of virtual objects on the triangulation point. In this way, the local coordinate system of virtual objects would match with OptiTrack coordinate system (see Figure 4.2).

⁸<https://github.com/tom-weiland/RiptideNetworking>

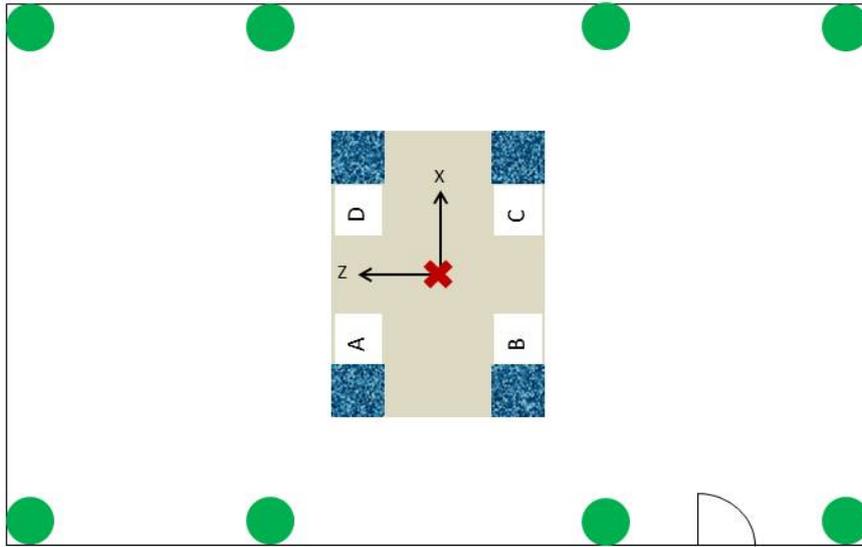


Figure 4.2: This room diagram shows using triangulation of four markers to overlap and match the coordinate system in HoloLens to the OptiTrack coordinate system. The red cross represents the center point of the room and also the origin of two coordinate systems. Eight green dots are the positions of OptiTrack cameras.

5 Evaluation

To assess the usability of PCTI in MR, a user study is necessary after the implementation. A user study can help us to get some feedback and task results to find out the defects within the system. By overcoming these defects, the PCTI can get further improvements and also increase the usability.

The hypotheses for the user study are as follows:

H_1 : Compared to hand interaction, the PCTI has better performance.

H_2 : The PCTI provides a good UX to the users.

5.1 Study Setup

The user study took place in a laboratory room where eight OptiTrack cameras were distributed around. Eight cameras are aimed toward the center of the room. The triangulation cardboard was placed in the center of the room (see Figure 4.2). As a workbench, the table was located on the positive Z-axis of the OptiTrack coordinate system. There was a marker on the table which was used as an anchor to ensure our tasks appeared on the workbench (see Figure 5.1). Next to the

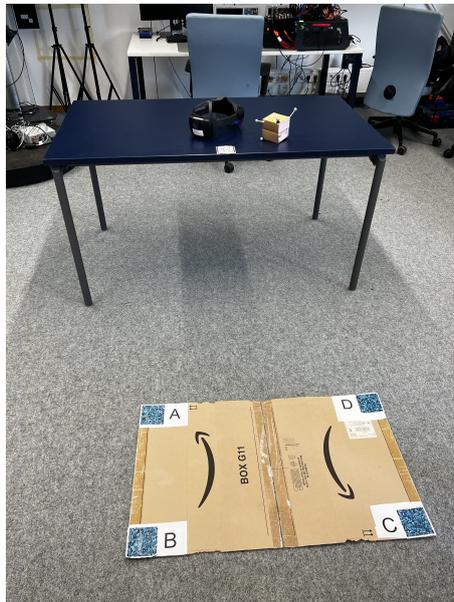


Figure 5.1: The configuration of user study. It consists of table, HoloLens 2, tangible cube, triangulation cardboard, anchor marker, laptop, and OptiTrack cameras



Figure 5.2: Tasks for the user study.

workbench, a laptop was placed on another desk which was used to run the server in order to realize data streaming. The last things were the most important devices of the experiment, HoloLens 2 and PCTI.

To compare the PCTI with hand interaction, we designed five tasks. When the task is assigned to the users, two virtual objects would appear on the workbench. The object with color texture is for manipulation, and the other one with transparent texture is the target. The aim of the five tasks is to use PCTI or hand interaction to manipulate the object, such as moving, rotating, and resizing, so that the manipulated object can overlap the target and match it as perfectly as possible. Once the task starts, a stopwatch is triggered to time until the task is complete. Audio would be played to inform the users after they achieve the task. In each task, we set up various items as the manipulated objects and the targets, such as cups or flowers. The position, rotation angle, and size of the manipulated objects and the targets are totally different. To reduce the learning effect on the results, we put the tasks in random order per participant and per interaction. In addition to this, the order of interactions is randomized for each participant as well.

Apart from time measurement for performance analysis, we prepared NASA Task Load Index (NASA-TLX)⁹ and System Usability Scale (SUS)¹⁰ to analyze PCTI in different aspects. NASA-TLX is used to measure perceived workload, including mental demand, physical demand, temporal demand, performance, effort, and frustration. As for SUS, it is a reliable tool for measuring usability.

There were 11 participants to attend the user study, 6 were male and 5 were female, from ages 21 to 38. Among the invited participants, there were 7 bachelor's or master's students, 3 doctoral candidates, and 1 postdoc. Most participants were in the field of computer science, and only 4 participants were from different fields. Four of eleven participants had experience in HoloLens and other AR HMD, three of eleven participants had never used HoloLens but had experience in other AR HMD, and the rest of the participants had no experience.

⁹<https://humansystems.arc.nasa.gov/groups/TLX/>

¹⁰<https://www.usability.gov/how-to-and-tools/methods/system-usability-scale.html>

5.2 Procedure

After the participant arrived at the laboratory, we briefly introduced the purpose and process of the user study to the participant and asked the participant to read and sign the consent form. The participant was then asked to stand behind the anchor markers on the table. The instruction on how to use the first interaction to manipulate virtual objects took around five minutes. After this, there was a trial to let the participant try out the interaction without any time limit. During the study, the participant was allowed to walk around the table to manipulate objects from different directions. The participant must execute five tasks in random order. First, we assigned the particular task through the server to the HoloLens. As long as the participant could see the task content, the task would get started and the stopwatch automatically started to run. The participant completed the task of object manipulation with the assigned interaction method, the stopwatch stopped and sent the time measurement to the server. If the participant thought the manipulated object fitted the target perfectly, but the successful determination didn't appear, then we judged the accomplishment manually and stopped the stopwatch. After finishing all the tasks, the participant was required to fill in a NASA-TLX questionnaire to assess the subjective mental workload of the interaction. The same study process would repeat again in the second interaction. The participant was taught how to use the second interaction, completed the task instances with the second interaction method, then again filled out a NASA-TLX questionnaire. In the end, a SUS questionnaire and demographics questionnaire were filled in. Any suggestion and feedback on PCTI could be indicated in this part. The entire user study took approximately one hour.

5.3 Result

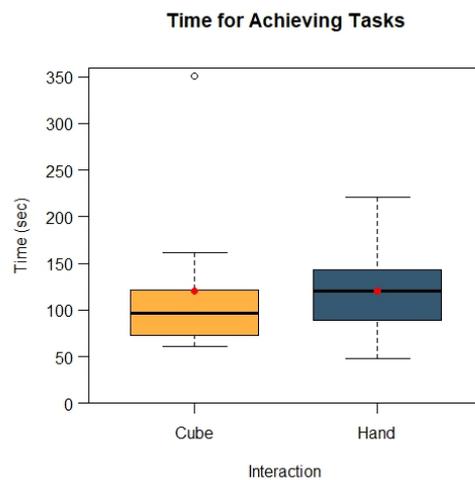


Figure 5.3: The box plot shows the average time of five tasks for each participant. The red dots represent the average time of 11 participants.

The results of manipulating time for PCTI and hand interaction are displayed in Figure 5.3. It shows the distribution of averaging time of five tasks (in seconds) to achieve the tasks. The red dots represent the average time of 11 participants. The only outlier in PCTI is due to the

wrong way of wearing HoloLens 2 which causes the participant to have poor vision to manipulate the virtual object. We can observe that except for the only outlier, using PCTI takes less time to accomplish the tasks. However, we performed the Independent Samples t-Test to compare the manipulating time in PCTI and hand interaction. If the outlier is included, The difference between PCTI ($M = 120.09, SD = 82.25$) and hand interaction ($M = 120.09, SD = 50.52$) is not statistically significant [$t(20) = 0, p = 1$]. If the outlier is removed, there is not a significant difference in manipulating time between PCTI ($M = 97, SD = 32.56$) and hand interaction ($M = 120.09, SD = 50.52$) as well [$t(19) = -1.23, p = .23$].

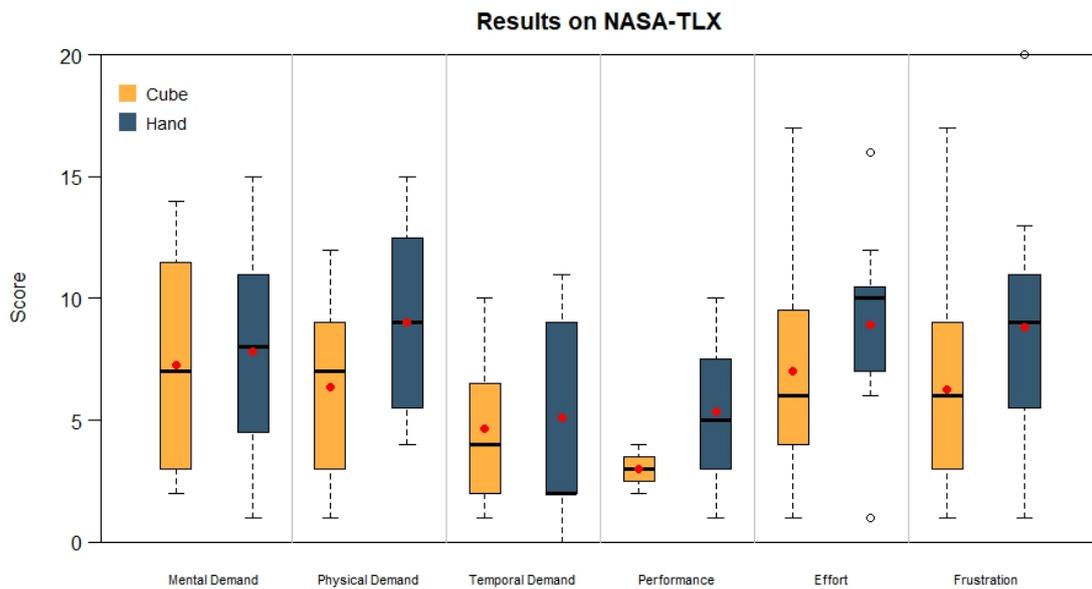


Figure 5.4: The box plot shows the NASA-TLX results. The red dots represent the average scores.

The box plot in Figure 5.4 shows NASA-TLX results for PCTI and hand interaction. The score is on an interval scale ranging from 0 (low) to 20 (high). The red dots represent the average scores. It is obvious that the average scores of PCTI in NASA-TLX six dimensions are less than the average scores of hand interaction. To be more precise, The Independent Samples t-Test shows a significant difference on Performance between PCTI ($M = 3, SD = .78$) and hand interaction ($M = 5.36, SD = 3.11$), [$t(20) = -2.45, p = .024$]. And there were no significant differences in rest of the NASA-TLX dimensions. The results are as follows: Mental Demand [$M = 7.27, SD = 4.69$ for PCTI, $M = 7.82, SD = 4.69$ for hand interaction, $t(20) = -.273, p = .788$], Physical Demand [$M = 6.36, SD = 3.83$ for PCTI, $M = 9, SD = 4.12$ for hand interaction, $t(20) = -1.554, p = .136$], Temporal Demand [$M = 4.64, SD = 3.04$ for PCTI, $M = 5.09, SD = 4.04$ for hand interaction, $t(20) = -.298, p = .769$], Effort [$M = 7, SD = 4.52$ for PCTI, $M = 8.91, SD = 3.83$ for hand interaction, $t(20) = -1.069, p = .298$], and Frustration [$M = 6.27, SD = 4.76$ for PCTI, $M = 8.82, SD = 5.12$ for hand interaction, $t(20) = -1.209, p = .241$],

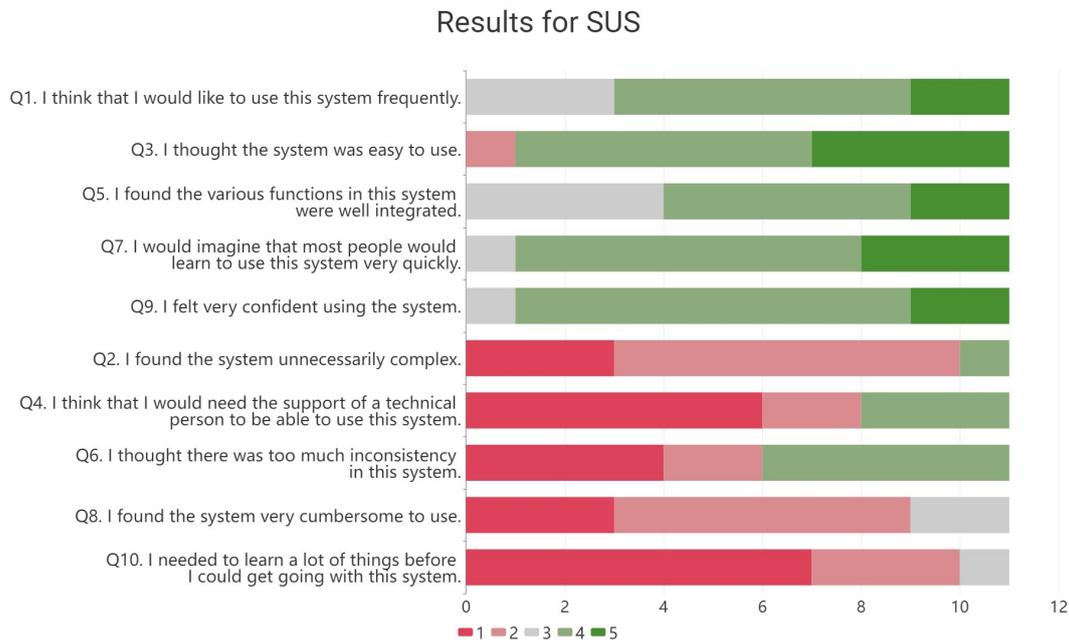


Figure 5.5: The SUS results.

The detailed results of SUS for PCTI presents in Figure 5.5. The original score for each of the questions is on an interval scale ranging from 1 (strongly disagree) to 5 (strongly agree). Odd-numbered questions are in a positive tone. By way of contrast, even-numbered questions are in a negative tone. With a series of calculations, the mean SUS score of all participants is 79.5 with an interquartile range (IQR) from 65 to 88.8. Our result is above average score of 68.

Some participants mentioned that the manipulation of the PCTI was not very smooth enough. The cube tracking was sometimes lagging, like some delay or interruption. The inconsistent tracking caused sometimes nothing happens to the virtual object when the participants moved the cube around. One of the participants said in order to have a smoother operation, the cube needed to be held in a correct way. Some participants referred to switching mode. When the cube was switched from Scale Mode to Move Mode, sometimes the size of the virtual object would be changed a little bit. In other words, mode switching sometimes caused unwanted movement, rotation, or scaling. One of the participants thought that it was hard to switch the modes when the position of the hands and the cube was in a particular posture, especially from Move Mode to Scale Mode. Many participants demonstrated their interests and positive attitudes toward the PCTI. Compared to hand interaction, it was beginner friendly and more intuitive. Using a cube to move and rotate the virtual object was easier than using gestures. Furthermore, A good point of the PCTI was the physical exertion was not that high, and the arms were always relaxed. One of the participants thought that it was simple and natural to use the cube. The interaction design of two modes in the cube made it easy to manage, while in hand interaction the participant at times struggled with thinking, moving, and locating on edges or corners.

5.4 Discussion

5.4.1 Efficiency

For the completion time of the tasks, our first hypothesis H_1 is not supported by the results. With or without the outlier, the completion time in PCTI is not significantly less than the time in hand interaction, although the overall time in PCTI is less and equal to the overall time in hand interaction. This result is in alignment with the study from Bozgeyikli and Bozgeyikli [BB21]. We think that the most possible factor is because of the lagging of cube tracking. Even though the PCTI improved the rotation problem of hand interaction which increases the efficiency of object manipulation. However, the lagging of cube tracking nullifies the benefits of this advantage. Inconsistent tracking prompts the participants to spend more time completing a movement at times.

It is noteworthy that excluding the outlier, most of the HoloLens 2 beginners performed better in PCTI than in hand interaction. For those who have never accessed HoloLens 2 before, it is not easy using hand rays to aim at the virtual object, especially aiming at the rotate handles and resize handles. Two of the participants stated that the operation of the pinching gesture was not smooth for them. The smaller aimed object leads the participant to spend more effort controlling it. Nevertheless, it is not a tricky problem for the participants with HoloLens 2 experience.

We compare the average time of 11 participants in the different tasks. The results show that participants spend less time accomplishing each task by using PCTI than hand interaction, except for task 4. We suppose the reason behind this can be the appearance of the manipulated object. The manipulated object in task 4 is a dark-colored shoe. Without the assistance of the bounding box, the contour of the dark-colored shoe can not be very obvious in our laboratory room compared to other light-colored items. Thus, participants may need to take more time to determine whether the manipulated object matches the target or not.

5.4.2 Mental Workload and Usability

The score of PCTI in each NASA-TLX dimension is less than the score of hand interaction, and Performance is the only one that PCTI is significantly more perfect than hand interaction. To be more precise, PCTI gives participants more confidence to accomplish the task. We think the factor that may have contributed to this situation is the intuitive manipulating method of the cube. The movement of the virtual object is directly mapped from the movement of the cube. The participants don't need to struggle aiming at the object or thinking about how to move and rotate the object. Nonetheless, there is no data showing that the perceived performance is a positive correlation to the actual performance. The scores of Mental Demand and Temporal Demand between PCTI and hand interaction are very close. It indicates that most participants had similar mental and perceptual activities for both interactions. They didn't feel much time pressure during the tasks.

According to our SUS score, the PCTI can be seen as a good usability system, but there is still some improvement need to be done [BKM09]. In summary, our second hypothesis H_2 is supported by the results of NASA-TLX and SUS.

6 Conclusion, Limitations, and Future Work

In the final chapter, we summarize the work done to develop PCTI, list the limitations of the system, and propose some future work to make the system more complete.

6.1 Conclusion

In this thesis, we presented a PCTI which can move, rotate, and resize the virtual object in an MR environment. The related work first shows how other research realizes TUI in immersive HMD and explores various designs of tangible props in paper materials or for object manipulation. Based on previous research, four preliminary prototypes of the PCTI were designed. We picked the Boob Cube prototype as the final prototype as it provided more flexibility and scalability than other prototypes. While implementing the TUI, losing track of the cube caused lower performance than expected, so we replaced the Vuforia image tracking with Opitrack optical tracking to improve the tracking precision. To assess the usability of the interface, we evaluated the TUI with hand interaction in HoloLens 2.

The results showed that PCTI had no significantly better efficiency on object manipulation than hand interaction. As for user experience, PCTI brought less mental workload to users than hand interaction. It made users more confident and satisfied with the results of their work. Overall, PCTI provided good usability on object manipulation in HoloLens 2.

6.2 Limitations

The main limitation of the interface is cube tracking. So far there is no tracking technique that can satisfy the conditions of high accuracy and low budget at the same time. Even though optical tracking has unmatched accuracy to detect slight movements, this tracking technique still cannot satisfy several users on object manipulation, not to mention the Vuforia image tracking with less accuracy. Besides, the tracking issue sometimes causes unexpected movement or scaling on the virtual object when switching modes.

Another limitation is that few participants could not accomplish the tasks. Although the virtual object looked almost fit with the target, a minor error still existed so that the manipulation could not achieve the successful conditions. To overcome that, we can either perform the user study with more participants or display a text next to the target to give some hints about achieving the tasks. Alternatively, provide simpler tasks for the user study.

6.3 Future Work

The improvements that could be made to PCTI are the manipulation of multiple objects. Currently, the interface is only implemented on the object manipulation of a single object. To improve the usability of the interface, add the functionality of object selection to the interface. Object selection provides not only the availability of manipulating multiple objects but also the probability to extend more functionality, such as deleting an object.

Due to the space restriction, our user study only compares the object manipulation in which the virtual objects are nearby the users. To have more complete comparisons, it is justifiable to have further evaluation of the object manipulation in long-distance objects.

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All links were last followed on August 12, 2022.

A Appendix

A.1 User Study Data

ID	Task 1	Task 2	Task 3	Task 4	Task 5
1	01:04	05:16	00:49	05:35*	00:45
2	01:07	02:44	01:38	01:56	00:44
3	04:17	04:08	02:44	16:25	01:39
4	00:40	01:20	01:07	04:13*	01:02
5	00:31	01:03	00:30	01:09	01:50
6	01:45	00:50	00:22	01:44	01:31
7	01:03	01:47	01:36	00:55	02:24
8	02:21*	05:04*	00:30	02:10*	01:48
9	01:00	00:52	00:24	01:52	01:45
10	01:37	00:38	01:24	01:45	00:29
11	04:33	00:52	00:38	00:43	01:20

Table A.1: Task completion time of the user study by using PCTI. The data are displayed in *mm : ss* format. If there is an asterisk behind the time, it represents that the participant thought the manipulated object fitted the target perfectly, but the successful determination didn't appear.

ID	Task 1	Task 2	Task 3	Task 4	Task 5
1	05:53*	00:34	00:33	01:31	00:55
2	06:00	01:25	02:25	01:38	02:49
3	02:46	02:27	01:28	02:23	02:33
4	00:48	02:07	00:44	02:52	01:33
5	00:30	01:01	01:02	00:42	00:44
6	02:13	03:16	00:30	03:02	01:04
7	01:28	02:54	05:17	01:17	01:17
8	03:10*	05:20*	03:37	02:08*	04:12*
9	02:01	01:07	01:05	00:55	01:40
10	03:31	03:41	00:56	01:11	01:19
11	00:28	01:17	00:46	01:07	00:51

Table A.2: Task completion time of the user study by using hand interaction. The data are displayed in *mm : ss* format. If there is an asterisk behind the time, it represents that the participant thought the manipulated object fitted the target perfectly, but the successful determination didn't appear.

ID	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration
1	7	7	5	3	5	9
2	12	10	6	3	11	9
3	11	5	9	4	10	10
4	13	4	2	4	6	6
5	3	8	7	2	4	3
6	2	2	2	3	3	4
7	14	12	3	4	17	17
8	4	1	1	2	9	3
9	2	2	10	3	4	1
10	9	11	4	3	7	6
11	3	8	2	2	1	1

Table A.3: NASA-TLX score of PCTI. The score is on an interval scale ranging from 0 (low) to 20 (high).

ID	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration
1	5	4	9	3	6	9
2	9	14	8	2	10	9
3	9	14	9	3	11	6
4	13	4	2	10	12	12
5	1	6	2	1	1	1
6	3	7	2	10	7	8
7	15	15	0	8	16	20
8	8	9	2	5	8	5
9	4	10	9	7	10	10
10	14	5	11	6	10	13
11	5	11	2	4	7	4

Table A.4: NASA-TLX score of hand interaction. The score is on an interval scale ranging from 0 (low) to 20 (high).

ID	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
1	3	2	4	2	3	4	5	2	4	1
2	3	2	4	4	3	4	4	3	4	2
3	4	4	4	4	3	4	3	2	4	3
4	4	2	5	1	4	1	4	2	4	2
5	4	1	4	1	5	1	4	2	5	1
6	3	1	4	1	4	4	4	2	3	1
7	4	2	5	1	4	4	5	2	5	1
8	5	1	4	2	5	2	5	1	4	1
9	4	2	5	1	4	1	4	1	4	1
10	4	2	2	4	3	2	4	3	4	2
11	5	2	5	1	4	1	4	1	4	1

Table A.5: SUS score of PCTI. The score is on an interval scale ranging from 1 (strongly disagree) to 5 (strongly agree).

A.2 Statistical Data

Independent Samples Test										
		Levene's Test for Equality of Variances			t-test for Equality of Means				95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Time	Equal variances assumed	.624	.439	.000	20	1.000	.000	29.188	-60.885	60.885
	Equal variances not assumed			.000	16.565	1.000	.000	29.188	-61.705	61.705

Figure A.1: The statistical results for task completion time with the outlier.

Independent Samples Test										
		Levene's Test for Equality of Variances			t-test for Equality of Means				95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Time	Equal variances assumed	1.474	.240	-1.230	19	.234	-23.091	18.770	-62.377	16.195
	Equal variances not assumed			-1.256	17.231	.226	-23.091	18.386	-61.842	15.660

Figure A.2: The statistical results for task completion time without the outlier.

Independent Samples Test										
		Levene's Test for Equality of Variances			t-test for Equality of Means				95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
MentalDemand	Equal variances assumed	.095	.761	-.273	20	.788	-.545	2.000	-4.717	3.626
	Equal variances not assumed			-.273	20.000	.788	-.545	2.000	-4.717	3.626
PhysicalDemand	Equal variances assumed	.073	.790	-1.554	20	.136	-2.636	1.696	-6.175	.902
	Equal variances not assumed			-1.554	19.891	.136	-2.636	1.696	-6.176	.903
TemporalDemand	Equal variances assumed	5.060	.036	-.298	20	.769	-.455	1.524	-3.633	2.724
	Equal variances not assumed			-.298	18.590	.769	-.455	1.524	-3.649	2.740
Performance	Equal variances assumed	17.396	.000	-2.448	20	.024	-2.364	.966	-4.378	-.350
	Equal variances not assumed			-2.448	11.238	.032	-2.364	.966	-4.483	-.244
Effort	Equal variances assumed	.329	.572	-1.069	20	.298	-1.909	1.786	-5.635	1.817
	Equal variances not assumed			-1.069	19.484	.298	-1.909	1.786	-5.641	1.823
Frustration	Equal variances assumed	.001	.981	-1.209	20	.241	-2.545	2.106	-6.938	1.847
	Equal variances not assumed			-1.209	19.895	.241	-2.545	2.106	-6.940	1.849

Figure A.3: The statistical results for NASA-TLX scores.

Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

place, date, signature