Object Manipulation with Tangible User Interface for Head Mounted Augmented Reality Devices

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Abstract

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Recent advances in technology enabled a new generation of Augmented Reality (AR) development where the near seamless integration and interaction between computer generated virtual and real-world physical objects can be achieved in real-time. This maturation of AR technology resulted in consumer-level AR products. These products support user mobility in the physical world in two ways: the AR head mounted solution in the Microsoft HoloLens, and the handheld mobile device solution in the Google Tango. The head mounted solution has two main advantages: the immersive experience with stereoscopic display, and hands-free interaction with the AR world. The HoloLens supports object manipulation with Natural User Interface (NUI), with the inherent NUI shortcomings of lacking in precision and intuition. This thesis investigates approaches to remedy these shortcomings by integrating other user interface paradigms. The

availability of user's free hands and the limited display real-estate of the head mounted display suggested exploration of solutions based on Tangible User Interface (TUI) devices that can support the display of Graphical User Interface (GUI) widgets. This thesis explores the potentials of linking a popular mobile phone as a TUI device for HoloLens, designs GUI for the phone display, adopts results from related user interaction research, and implements a novel solution to overcome the HoloLens UI shortcomings. Results from user testing shows that although with no observable significant timing differences in completing object manipulation tasks, users do perceive the TUI solution as more efficient and effective. Moreover, they prefer manipulating object using TUI rather than NUI because they feel more engaged.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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Chapter 1. INTRODUCTION

Augmented Reality (AR) is a user interface metaphor, which allows for interweaving digital data with physical spaces[1]. AR evolves around the concept of overlaying digital data onto the physical world, typically in the form of graphical augmentations. These augmentations are registered in three-dimensional (3D) space and are interactive in real-time [2]. This enables the users of AR systems to interact with their physical and virtual environments instantaneously.

AR research has gone through great advancements over past decades. The most recent commercial product releases, e.g., the Google Tango devices, or the Microsoft HoloLens, are examples that the AR technologies are maturing and bringing their potentials for significant impacts to the public. As the field continues to develop, AR technologies are increasingly more capable of overlaying physical world with virtual objects. For example, marker based AR [3], table top AR [4] , and markerless AR [5].

The main interesting feature of the AR technology is the ability for the user to interact with the virtual object which not only overlay, but also interacts with the physical world. A critical area of study is in the understanding of the necessary support and implementation for interacting with virtual object in AR environment. For example, HoloLens used Natural User Interface (NUI) such as gaze, gesture, and voice as modalities for the user to interact with the virtual objects. Nevertheless, these subsets of NUI are sometimes not as precise as they are intended to be [6].

Take gesture recognition as an example, HoloLens recognizes a limited set of gestures for interacting with the AR environment. For HoloLens to identify the gesture, the user has to perform the exact gesture or the system won't recognize the gesture [7]. This means beginner users might find it awkward to realize that their tap gesture is not registered by the HoloLens because it is not the tap gesture that the device recognizes. Additionally, voice recognition in NUI faces a similar same problem because of the diverse pronunciations the same word [8]. Thus, the NUI is not really "natural" because users must repeatedly train the interface.

Tangible User Interface (TUI) is an interface that enables human and computer interaction using physical object/environment as input [9]. One of the most popular implementation of TUI for AR is the marker based tangible controller [10]–[13]. In this work, the implemented TUI has shown to be intuitive, engaging, and effective for manipulating virtual object in AR environment.

For example, TUI is intuitive because in Issartel's work [11] most of the test participant can completed the task successfully without any hint on how to manipulate the virtual object. Another example is Seidinger's research [12], which demonstrated that the TUI implementation to be more engaging to the user than the touch-screen approach. While Dünser [13] showed that their TUI implementation is more efficient in manipulating virtual objects for a desktop AR when compared to that of the mouse interface.

This thesis proposes incorporating TUI as an additional modality in AR for interacting with virtual contents. The implementation focuses on the strength of TUI to address the drawbacks in NUI. The goal is to further investigate the possibility of TUI from marker based tangible controller [12] to tangible controller with six Degree of Freedom (DOF) movement in AR environment.

The implementation will use modern smart mobile phone, equipped with touch screen interface, accelerometer and gyroscope sensors, as the tangible object which will support six DOF. The tangible object will be represented as a laser pointer in the virtual world, and the HoloLens user can control the laser pointer with the phone's gyroscope sensor. For manipulating virtual object, the sensors and/or the touch screen can be configured to support manipulation techniques in the AR environment.

This thesis presents the results from an initial testing of efficiency, attractiveness, and perspicuity based on manipulating virtual objects using the NUI and TUI in the same AR environment. The results from the user study suggest that the users perceive our TUI implementation to be more efficient than the default NUI.

This thesis first presents background research for the TUI design and implementation. The chapter following that introduces the study goals and the user study conducted. The implementation of the proposed solution is then described with a discussion of potential limitations. Chapter six presents the results of the user study with detailed discussion of observations and limitations. Lastly, the thesis concludes with a summary of potentials for future work.

Chapter 2. LITERATURE REVIEW

This work is focusing on the field of manipulating virtual objects in an AR environment based on TUI, and this section presents review of past research and implementation in these two areas. The goal is to identify problems and interesting opportunity.

2.1 AR

Sutherland reported their head-mounted 3D system, furnished with stereoscopic displays and head positional tracking capabilities, in 1968 [14]. Back then AR development was done in a controlled room inside a lab. Today, with rise of many mobile devices and advancement in AR technologies such as geo-location and spatial awareness [15], AR has move into the field.

This research in AR field focuses on user interfaces that enables viewing of digital content within the physical world. AR capable devices are able to overlay digital information, such as 3D virtual objects, on to the user's field of view of the physical world in real-time.

Most recently, mobile AR devices are becoming more advance by enabling the interaction of the virtual content with the real world, and apply the law of physics to the digital content [16], [5]. For example, a 3D sphere can be created in the middle of the user's living room, and the sphere is able to roll from on top of a table onto the floor as if the law of real world physics is acting on it. This opens a lot of possibilities and interesting research topics on how to improve the ability of these devices to provide more support and modalities for the users to interact with the digital content.

2.2 CURRENT AR TECHNOLOGY

One of the modern mobile AR devices that has the ability to simulate physics in AR is the Microsoft's HoloLens [17]. The HoloLens can scan a room where the user is in, and create virtual meshes that represents the room. The results of scanned room are the ability of HoloLens to make virtual objects interacts with the physical world in real-time, while enabling the user to move freely in the physical room. Microsoft has already implemented a set of User Interface (UI) to interact with the virtual content such as, creating, selecting, manipulating, and deleting, which utilize the

Natural User Interface (NUI) concept to implement gaze input, gesture recognition, and voice recognition [18]–[21] in the device.

2.3 THE USER INTERFACE FOR AR

NUI [22]is a relatively new concept of user interface in human and computer interaction design. The base concept is that the user can interact with the computer using natural and intuitive action that derives from everyday human behavior. Some examples of NUI are touch screen sensors, voice recognition, gesture recognition, and brain wave signal readers. Still, the most common interface used today for human and computer interaction is the Graphical User Interface (GUI) [23] and the Tangible User Interface (TUI) [9]. An example of GUI can be seen in any current computer programs today, such as buttons, icons, scroll bar, etc., which are displayed in the computer screen. To interact with these graphical interfaces, we use a well-known example of TUI, which is the mouse.

There are many past research on TUI in AR. They presented many variety of tangible controller, such as marker based tangible controller[12], device movement based tangible controller[24], and touch based tangible controller[25].

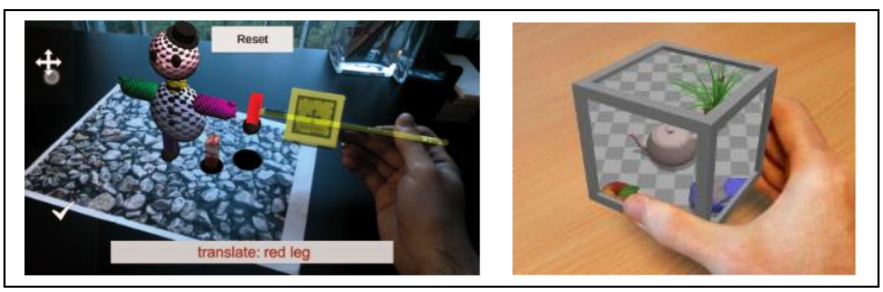

Figure 2.1. Example of Past AR and TUI combination (sources [11], [12]).

2.4 PAST AR AND TUI IMPLEMENTATION

Seidinger [12] implement their tangible controller using a stylus that has marker attached to it, so that the application knows the relative location and rotation of the tangible controller. Another example is T. Ha's implementation [26] in which they also use marker based tangible controller as a tool for object creation and manipulation in their AR environment. Most of the tangible controller solutions for AR environment are still using the marker based concept. Figure 2.1 shows some of the past TUI implementation for AR, image on the left is an example of marker based TUI in which the implementation is using a stylus as tangible object, and the image on the right is an example of movement based TUI in which the implementation is using a cube as the tangible object.

Chapter 3. STUDY GOALS

Although NUI has a promising advancement in its research and application, the implementation of NUI still has some drawbacks. NUI, such as gesture or voice recognition is not yet intuitive [6], meaning not every user will be able to reproduce the predefined gesture or speech without enough practice. For example, in HoloLens to interact with the virtual content a user can use a tap gesture to do most of the task, the problem with the predefined tap gesture is that people have diverse ways of doing the tap gesture. Ergo, unless the user does the exact tap gesture that the HoloLens can recognize other variation of the tap gesture will not be registered as a tap.

3.1 Opportunity Presented

This project will combine the concept of device movement based and touch based TUI to create a marker less tangible controller with six Degree of Freedom (DOF), similar to Graf‘s implementation[24]. The differences are that this project tangible controller is used in AR environment. The reason that this study is interested in head mounted AR display is because head mounted has the advantage of stereoscopic display and free hands available to hold a controller.

3.2 Proposed Solution

With these drawbacks in NUI, there might be some available solution in TUI and its advantage that could help overcome these NUI disadvantage. Tangible interaction enables more effective and efficient sequences of actions for the user to complete their goal [27]. The tangible approach allows the creation of intuitive interfaces, and providing users with a strong feeling of directness [28]. Microsoft HoloLens already has a built in NUI, which is the gesture recognition, voice recognition, and gaze tracker. Unfortunately, some people experience difficulties [29] when trying to interact with the virtual object using the NUI's modalities. So, this study is taking the advantages of TUI to improve AR interaction experience in HoloLens by adding support for Tangible User Interface (TUI). The proposed solution is implementing a tangible controller to interact with the virtual object in the AR environment of the HoloLens.

3.3 PROPOSED STUDIES

To verify the correctness of the proposed solution, this thesis implements a TUI support for HoloLens AR. Then, conduct a study of users' interaction with test cases, and verify if the proposed solution is better.

The TUI is considered better if it is significantly more efficient, attractive, or perspicuous. To test if the implementation is more efficient quantitatively, this study conducted a user test to see if user can complete specific task, and compare the completion time of each task using the two different UI (NUI and TUI). To get a more convincing result, this study will use a well-defined user experience questionnaire to get qualitative result from the user subjective view of each UI in terms of efficiency, attractiveness, and preciousness.

The qualitative and quantitative results are analyzed to find any significant difference, so that the study can discuss the success of the proposed solution, existing limitation, and potential future work.

Chapter 4. USER STUDY

We conducted a user study to test built-in gesture recognition for manipulation and selection (the NUI) with the proposed solution, the mobile phone tangible controller (the TUI). The goal is to compare the efficiency, attractiveness, and perspicuity between TUI and NUI implementation in object selection and manipulation. The manipulation techniques will consist of translating, rotating, and scaling of the virtual object in the AR environment, which are the three basics way of direct manipulation of an object.

4.1 DETAILS

To test for efficiency, this thesis adapts the method used by Marzo et al. [30], in which each task is measured in Task Completion Time (TCT). For accurate timing of TCT, the test was using A 3D docking method introduced by Zhai et al. [31]. In his work, Zhai implemented a 3D docking target to measure the accuracy of 3D object placement when using 6 DOF input device. To test attractiveness and perspicuity we use a user experience questionnaire (UEQ) adapted from [32], which is fill out by the tester after each experiment to obtain their subjective view of the user interface.

The study involved 27 graduate and undergraduate Computer Science (CS) students from University of Washington Bothell. The reason we chose CS students is because they have technological knowledge, and recognize some concept of AR. But, the volunteers that were chosen are first time user of the Microsoft HoloLens along with the tangible controller.

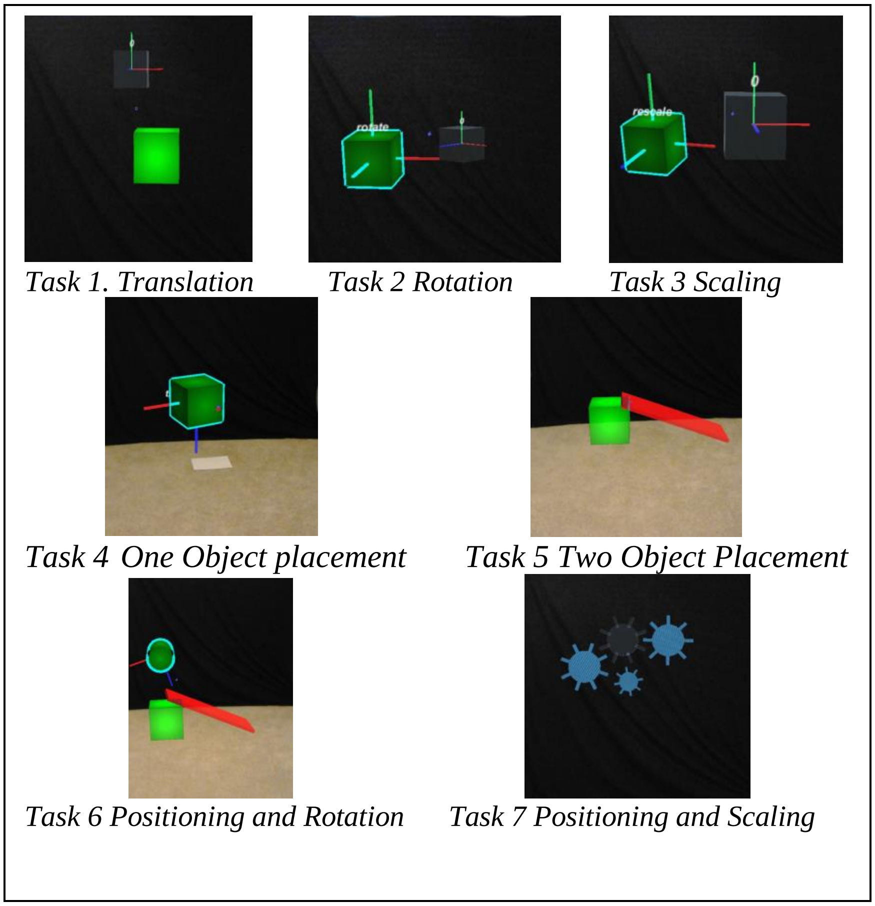

Figure 4.1. Task 1 through task 7 illustration.

4.2 TASKS

As shown in Figure 4.1, seven tasks are derived for the purpose of comparing the HoloLens NUI and our proposed TUI. A user is to complete all seven tasks in both user interface implementations. The seven tasks are categorized into: basic, advanced, and combination of manipulations.

4.2.1 *Basic Manipulations*

The top row of Figure 4.1 depicts the basic manipulation tasks—to find out if the user is able to perform the three most basic manipulation techniques, translating, rotating, and scaling.

- Task 1. As shown in the top row left screenshot of Figure 4.1, the user has to move the green box, generated in the center of the room, into a given position indicated by the transparent box as the docking target in an arbitrary 3D position. For NUI, the task involves gaze and pinch gesture to select, and hold the pinch gesture to keep selecting and moving the arm in the direction needed to translate the object. Users can also move in the AR space while hold the pinch gesture to move the object. For TUI, this involve pointing the controller towards the object and press the select button to select an object. Next, use the UI in the controller to translate the object, the UI includes gyroscope input and touch screens. To start the timer for the task the user must say the word “start”, and the timer above the docking target will start. To complete the task and stop the timer, the user has to translate the green box to the position of the target until the target turns yellow indicating that the green box is translated correctly (predefined range of error tolerance of 1 cm of each axis).

- Task 2. As shown in the top row middle screenshot of Figure 4.1, the user has to rotate the same green box until the same rotation, which is shown by the orientation axis in the docking target, is achieved. For NUI, the task involves selecting the object using the same method in Task 1. However, the user has to say the word “rotate” first to change the UI mode from “translate” to “rotate”, then the user can move the arm to rotate the object accordingly. For TUI, the task also involves the same way of selecting the object using TUI, then press the mode button to change the mode from “translate” to “rotate”, and use the same UI in the controller to rotate the object. To start the timer for the task the user must say “start”, and the timer above the docking target will start. To complete the task and stop the timer, the user has to rotate the green box to match of the rotation of the target until the target turns yellow indicating that the green box is rotated correctly (predefined range of error tolerance of 1 degrees of each axis).
- Task 3. As shown in the top row right screenshot of Figure 4.1, the user has to scale the same green box until it has the same size with the target’s size. For NUI, this task involves changing the mode to scale by saying “scale”, and use the same gesture to select while move the arm left or right to scale the object. For TUI, the task involves changing mode of manipulation to scale by pressing the green button again, and use the touch screen to scale the object. To start the timer for the task the user must to say “start”, and the timer above the docking target will start. To complete the task and stop the timer, the user has to rescale the green box to the size of the target until the target turns yellow indicating that the green box is rescaled correctly (predefined range of error tolerance of 1 cm of each axis).

If the user has successfully finish the task, it implies that the user can do manipulation with precision.

4.2.2 *Advance Manipulations*

The middle row of Figure 4.1 depicts the more advance manipulation tasks—for the user to arrange virtual objects with specific targets in the AR environment, and to know if the user understand the concept of AR.

- Task 4. The user is asked to move the green box to a specific place in the test environment. At the start of the test, the environment spawns a green box at a random location. Next, the tester asked the user to move the box from that arbitrary location to the center of the room. To start the timer for the task the user must say "start", and the floating timer will start. To complete the task and stop the timer, the user has to place the green box in the center of the room indicated by a paper marker and say "stop". The tester then evaluates from the live streaming video if the green box is properly placed. If the user has not properly place the box, the user will then be asked to resume the timer again by saying "start", and asked to properly place the green box. The task is successful if the box is properly place in the marker, similar to what the middle row left screenshot of Figure 4.1 shows.
- Task 5. The user is asked to create a ramp like structure using the green box and a red plank. At the start of the test, the environment spawns a green box and a red plank at a random location. Next, the tester asked the user to create the ramp structure in the center of the room. To start the timer for the task the user must say "start", and the floating timer will start. To complete the task and stop the timer, the user has to show the completed structure and say "stop". The tester then evaluates from the live streaming video of the HoloLens if the structure is properly created. If the user has not properly place the box, the user will then be asked to resume the timer again by saying "start", and asked to properly create the structure. The task is successful if the structure is like that of a simple ramp, as shown in the middle row right screenshot of Figure 4.1.

For these tasks, both TUI and NUI, the user has to use the manipulation technique learned from previous tasks to complete it. If the user can finish these tasks, it implies that the user can arrange any virtual object in similar AR setups.

4.2.3 *Combine Manipulations Techniques*

The last row of Figure 4.1 depicts more advanced tasks adapted from [33]. The goal is to find out if the user can perform combination of manipulation techniques. If they have successfully completed these basic combination of techniques, it implies that the user is able to do most combination of manipulation techniques for manipulating virtual object in AR environment.

- Task 6. The user has to roll the green cylinder on the ramp they had created from Task 5 by using translate and rotate manipulation technique. At the start of the test, the environment spawns a green cylinder at a designated location. Next, the tester asked the user to roll down the green cylinder on the ramp structure in the center of the room, which was created in the previous task. To start the timer for the task the user must say "start", and the floating timer will start. To stop the timer, the user has to say "stop". The tester then evaluates from the live streaming video if the cylinder is properly rolled. If the user has not properly roll the cylinder, the user will then be asked to resume the timer again by saying "start", and asked to properly roll the cylinder. The task is successful if the cylinder rolls from the top end of the ramp to the bottom end of the ramp. The last row left screenshot of Figure 4.1 shows the scenario of the task.
- Task 7. The user has to align the smaller gear in between the two larger ones, depicted by transparent docking target, so that they appear connected by using translate and scale manipulation technique. At the start of the test, the environment spawns three gear like objects at a designated location. Next, the tester asked the user to match the size and the position of the small gear with the target. To start the timer for the task the user must say "start", and the floating timer will start. To stop the timer, the user has to match the size and position until the target turns yellow. The task is successful if the transparent docking target turns yellow. The last row right screenshot of Figure 4.1 shows the scenario of the task.

4.3 PROTOCOL

This section will describe the protocol of the user testing phase for both NUI and TUI implementation. At the start of the test, subject is given direction on how to select an object, manipulate an object, and change between manipulation techniques during the test. Next, the subject was given 3 minutes time to practice and understand the user interface. When the subject is ready, the test commences, starting from task 1 and following in order. During each test, the subject was timed using a timer to get the TCT of each task. After finishing the first user interface (either NUI or TUI) the subject was given a break time until they finished answering the UEQ for the UI he/she just finished testing. Then, the subject continues to test the next user interface implementation, doing the same tasks in order. Then finally, answers the same UEQ for the last UI implementation that he/she had just tested. The following section will discuss each phase of the user testing. Figure 4.2 shows the user during testing.

4.3.1 *Phase 0*

This phase is where the both NUI and TUI get feedback from initial tester about the usability and design of the test application interface. In this phase, none of the testers are timed, because the goal is to get users feedback about initial prototype of the UI, and evolve the design of the UI so that it is more usable.

4.3.2 *Phase 1*

Phase 1 is where the timed test for the 7 tasks begin. The protocol for testing phase 1 is as described in previous section of this chapter. In Phase 1, the users are given the NUI implementation first, then the TUI implementation next. The data collected for phase 1 is from 15 volunteered subjects. After analyzing data of testing phase 1, we found out that we should do phase 2 of the user testing to compare if the order of which UI is given first matters.

4.3.3 *Phase 2*

For this phase, the test is done using the same protocol of phase 1. The difference is that the subject is given TUI first at the start of the test then the NUI next, and the subject only need to do task 1 to task 3. Because from the data collected from phase 1 only Task 3 is significant the data collected for phase 2 is 12 volunteered subjects.

Chapter 5. IMPLEMENTATION

The system consisted of three main components: the test environment, the built-in NUI, and the tangible controller. Tangible controller and the environment need to have network support for transferring and receiving data. The system can transfer the data from the tangible controller to the AR device asynchronously with minimum delay in response to improve usability of the controller. The system also supports multiple platform build of some of the most popular mobile devices operating system (iOS, Android, and Windows).

Figure 5.1. Microsoft HoloLens (left), Windows Phone (right).

The implementation is using the HoloLens, Figure 5.1 left, as AR head mounted display and a Windows mobile phone, Figure 5.1 right, as the tangible controller, as they both have similar network support and build under the same Software Development Kit (SDK). Unity and Windows 10 SDK was used as the development environment for this system, because Unity already has a support for multi-platform system build and AR development.

The data sent from controller to the HoloLens are through User Datagram Protocol (UDP). This protocol was implemented to reduce the latency of data transferring between devices, since UDP is not considering lost packet during transmission. By reducing latency, the interaction using the tangible controller would seem real-time.

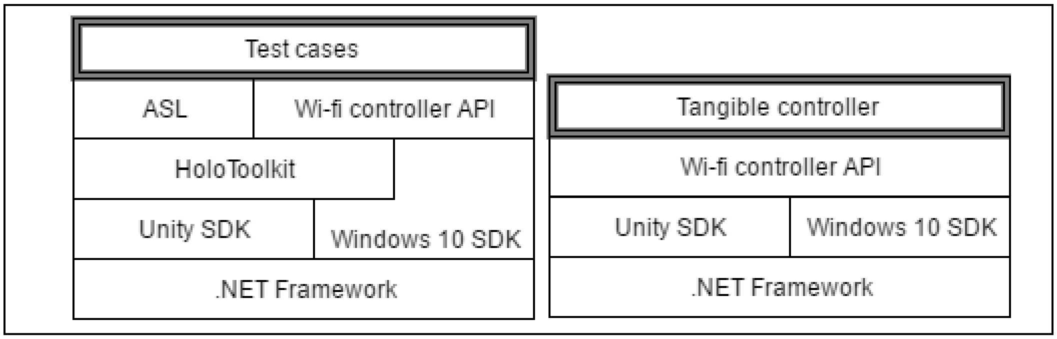

Figure 5.2. Implementation library supports: Test cases (left) and Tangible controller (right).

5.1 Test Environment & Built-In NUI

For the test environment, Figure 4.1 shows each of the test cases running, we implement it in the HoloLens to test the user interface interaction in AR space, UDP server to receive data from the TUI, and enabled the built-in NUI for object interaction in the testing environment. The HoloLens is also using Wi-Fi controller API to process all the sensor data coming from the tangible controller. All of the AR implementations and the solution building in the HoloLens device were using the HoloToolKit provided by Microsoft, which enables Unity to build and develop AR application for the device. This HoloLens system application is utilizing Augmented Space Library, which was develop by Dr. Sung's project group prior to this research.[1] Figure 5.2 left side depicts the architecture hierarchy of the HoloLens system implementation.

The NUI design for gaze, gesture, and voice[2] is adopting the guide line and tutorial provided by Microsoft development forum [3]. The Wi-Fi controller API is downloaded from a resource found in Unity asset store.

5.2 Tangible Controller

For the tangible controller, we implement UDP client to send data over the network to the HoloLens, and using the Wi-Fi controller API to gather all the sensor data, such as gyroscope and touch gestures. The phone application was also built using Windows 10 SDK, as the tangible controller used is a Windows phone. Nevertheless, the tangible controller solution is cross-

[1] http://depts.washington.edu/csscts/CRCS/
[2] https://youtu.be/BinnzBbsJ-U
[3] https://developer.microsoft.com/en-us/windows/mixed-reality/holograms_210

platform, and can be built to any mobile devices with any of the three most popular operating system (iOS, Android, or Windows). Figure 5.2 right side depicts the architecture hierarchy of the tangible controller system implementation.

For this implementation of creating a 6 DOF tangible controller[4], we have decided to use a mobile phone as the tangible object because it is a powerful device which is already equipped with multiple sensors [34]–[36], which will enable the capability of 6 DOF without any marker. The implementation is going to use sensors such as gyroscope, accelerometer, and touch-screens. The sensor data is then sent to the HoloLens through Wi-Fi network. The tangible controller is represented as Laser Pointer Interaction Interface [37] in the AR environment because it is intuitive [38]. Adding direct manipulation interfaces as feedback to user for usability [39], [40].

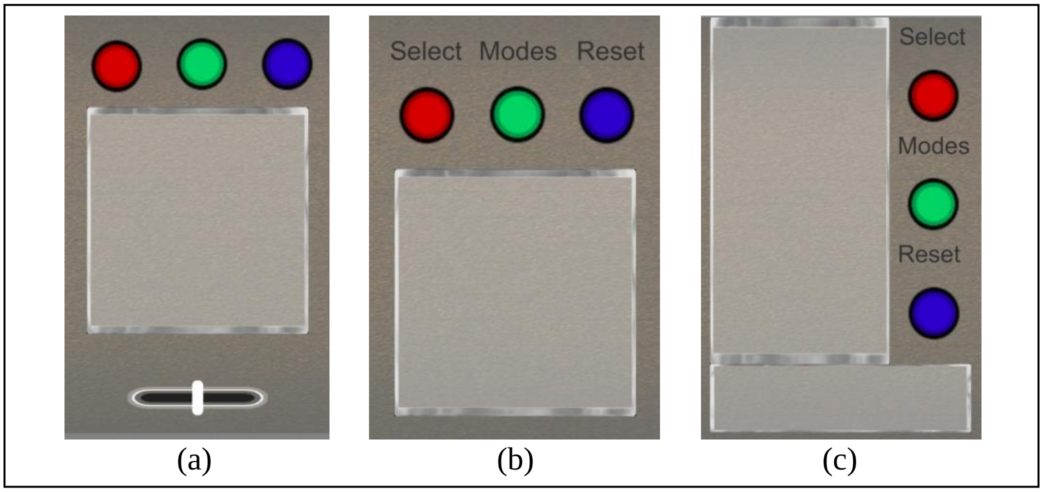

Figure 5.3. Evolution of tangible controller UI.

The UI on the touch screen of the mobile phone are mostly implemented using Unity UI canvas library. On the screen, there are three buttons and two designated touch pads. Each of the button has distinct color and functionality, as shown in Figure 5.3 (c), red button is to select the object, green button is to change mode between translating, rotating, or scaling in cycle, and the blue button is to calibrate the orientation of the laser pointer, and to rotate the object using the absolute rotation of the phone. The organization of button on the right side of the screen is assuming that the user is right handed. The touch screen zone is implemented to give user a way to manipulate the object incrementally. There are two different touch zones because there are 3

[4] https://youtu.be/1LzR0gLyKgE

axes in 3D AR space and there are only 2 axes in the touchpad. Thus, the larger zone is for manipulation in X and Y axis, where the smaller zone is for manipulation in Z axis. This implementation decided to use touch screens for manipulation because touch screens application is interactive, efficient, and convenient [41]. The buttons and touch screens are placed near to the bottom part of the mobile phone and closer to the thumb, because the bottom of the screen is the easiest to touch by the finger [41].

5.2.1 *Iteration 1*

This iteration is the first UI prototype design for the tangible controller, shown in Figure 5.3(a). The top three buttons have specific functionality. The red button is for selecting, the green button is for changing manipulation techniques, and the blue button is for calibrating the orientation of the tangible controller. For manipulation, translating object is utilizing the gyroscope from the mobile device, the touch screen zone in the middle is for rotating object using swipe gesture, and the slider bar is to rescale the object.

5.2.2 *Iteration 2*

Second iteration, shown in Figure 5.3(b), user echo feedback was added on top of each button to tell user the functionality of each button. Next, manipulation techniques are adapting similar source of input, for example, to do rotation user can use the touchpad for swipe and pinch zoom gesture, while to do scaling the user can use the touch screen and do the swipe gesture.

5.2.3 *Iteration 3*

For this iteration, shown in Figure 5.3(c), the three buttons are place in the right side of the screen for easier access using right hand thumb. Next, the pinch zoom gesture is removed from the implementation, and finally, this iteration implements absolute modes and incremental modes of manipulation for translating and rotating. In absolute mode, the manipulation is using gyroscope input, while incremental mode is using touch screen swipe gesture.

Chapter 6. RESULT AND DISCUSSIONS

This chapter discusses the results of the testing phases, beginning with phase 0 implementation evolution, and results of phase 1, phase 2, and the UEQ.

The collected results were analyze based on the Two-Sample t-Test with Unequal Variances to detect the significance in user timing differences.

6.1 PHASE 0 RESULT

The results from this phase caused the evolution of manipulation interface for NUI, and the UI design layout for TUI. Figure 5.3 shows the evolution of the UI of the tangible controller.

6.2 PHASE 0 DISCUSSION

Results of user testing from phase 0 indicated that the initial user interface for the NUI was difficult to master because each manipulation technique has its own specific interface where the knowledge from one is not transferable to the next. For the GUI design on the tangible controller, the users cannot remember the functionality of the buttons because of the lack of echo feedback.

Considering the feedback from the first implementation, the second iteration UI has a few changes. The user feedback from second iteration design is that the buttons are difficult to reach, and that the pinch zoom gesture for rotation is not intuitive. Additionally, the pinch gesture requires both hands, which violates the implementation goal of only needing one of the free hands from using the AR head mounted device.

After considering feedback from second UI iteration, the third evolution of the tangible UI was implemented. The new position of the buttons ensure that the user can reach them with a single hand, and the pinch zoom gesture is replaced with a slider area that can be operated with a single hand. Note that a well-defined and easy to use UI design requires much more research and usability testing. With our focus on understanding TUI support for AR in general, the UI design effort ended as soon as our test subjects are not confused or hindered by the interface.

6.3 Phase 1 Results

In phase one of the testing, users perform all seven tasks first based on NUI, followed by repeating the same tasks based on the TUI implementation. One of the users was unable to complete the tests because the NUI was unable to recognize that user's voice commands. The results associated with that user are not included.

Task Completion Time (TCT) is the time measured in seconds that the participants needed to complete each task. The TCT of tasks 1 to 3 and 7 are presented. Due to the inability of objectively collect TCT for tasks 4 to 6, the timing results for these tests are not included in the analysis. However, the users went through these tests as practice for completing task 7.

Table 6.1. Phase 1 Results

Average TCT (sec)	Task 1	Task 2	Task 3	Task 7	Total Task 1-3 & 7
TUI	16.94	46.54	8.84	55.54	127.871
NUI	17.55	48.02	33.79	79.16	178.529
p value	0.8429	0.9258	0.0051	0.053	0.0409

Table 6.1 shows the average of TCT of tasks 1 to 3 and 7; and the t-test results of comparing TUI and NUI timings. Notice the significant differences between TCT for task 3, and the total time, with $p<0.05$.

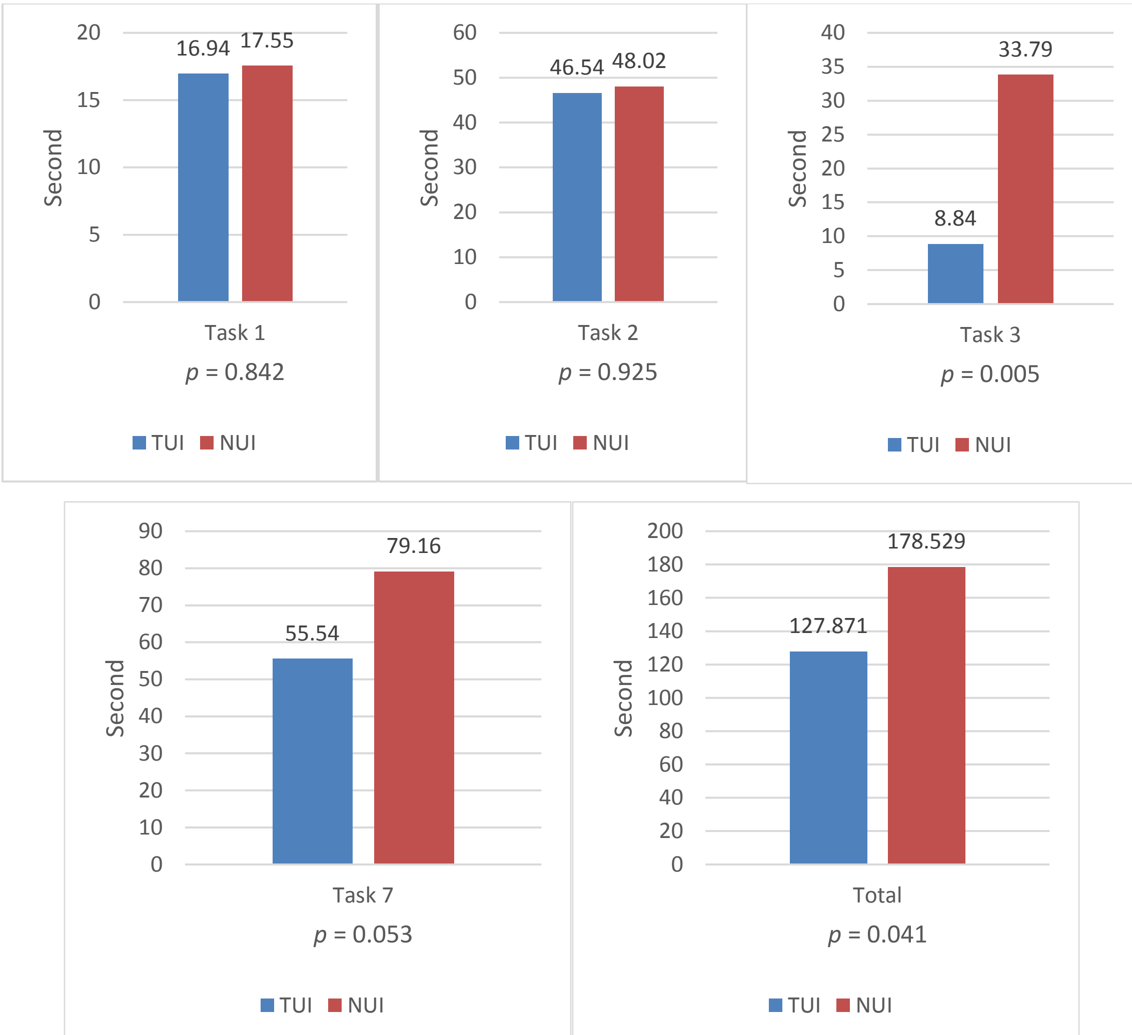

Figure 6.1. Comparing TCT time in Phase 1 for each task.

6.4 Phase 1 Discussion

Figure 6.1 shows the comparisons between TUI and NUI TCT for each task. Recall that tasks 1 and 2 are translation and rotation. The TCT results associated with these tasks do not show any significant difference between NUI and TUI.

Only the scale manipulation technique implemented in the TUI demonstrates significant difference when compared to that of NUI. Additionally. The total time of each tester performing all the tasks for TUI is also significantly faster than that from NUI.

The significant difference on Task 3, scaling, may be attributed to: first, user familiarity and intuitiveness of using a touch pad for scaling; second, the fatigue experienced by the user after performing long durations of gestures for NUI when attempting to complete tasks 1 and 2; and third, the NUI gesture for scaling is not natural or intuitive.

6.5 Phase 2 Results

Phase two of the test swaps the order of testing—TUI followed by NUI. The goal is to examine the relationship between TCT and the order that the user interface methods are tested. Correspond to this focus, only the first three basic object manipulation tasks: translate, rotate and scaling, or, tasks 1 to 3 are tested.

In the following, the results of phase one and two TCT are compared in Table 6.2 (for TUI) and Table 6.3 (for NUI). Table 6.4 compares the TCT, TUI vs. NUI, from phase two. Figures 6.2 and 6.3 plots the results from Table 6.2 and 6.3 in shades of blue for TUI and red for NUI while Figure 6.4 plots the results of Table 6.4.

Table 6.2. Phase 1 and Phase 2 comparison for TUI Results.

Average TCT (sec) TUI	Task 1	Task 2	Task 3	Total Task 1-3
Phase 1	16.94	46.54	8.84	72.32
Phase 2	20.09	54.94	5.19	80.22
p value	0.686	0.677	0.172	0.735

Table 6.3. Phase 1 and Phase 2 comparison for NUI Results.

Average TCT (sec) NUI	Task 1	Task 2	Task 3	Total Task 1-3
Phase 1	17.55	48.02	33.79	99.37
Phase 2	20.98	90.36	7.21	118.56
p value	0.558	0.036	0.008	0.337

Table 6.4. TUI and NUI comparison for Phase 2 Results.

Average TCT (sec)	Task 1	Task 2	Task 3	Total Task 1-3
TUI	20.09	54.94	5.19	80.22
NUI	20.98	90.36	7.21	118.56
p value	0.9167	0.1031	0.2094	0.1111

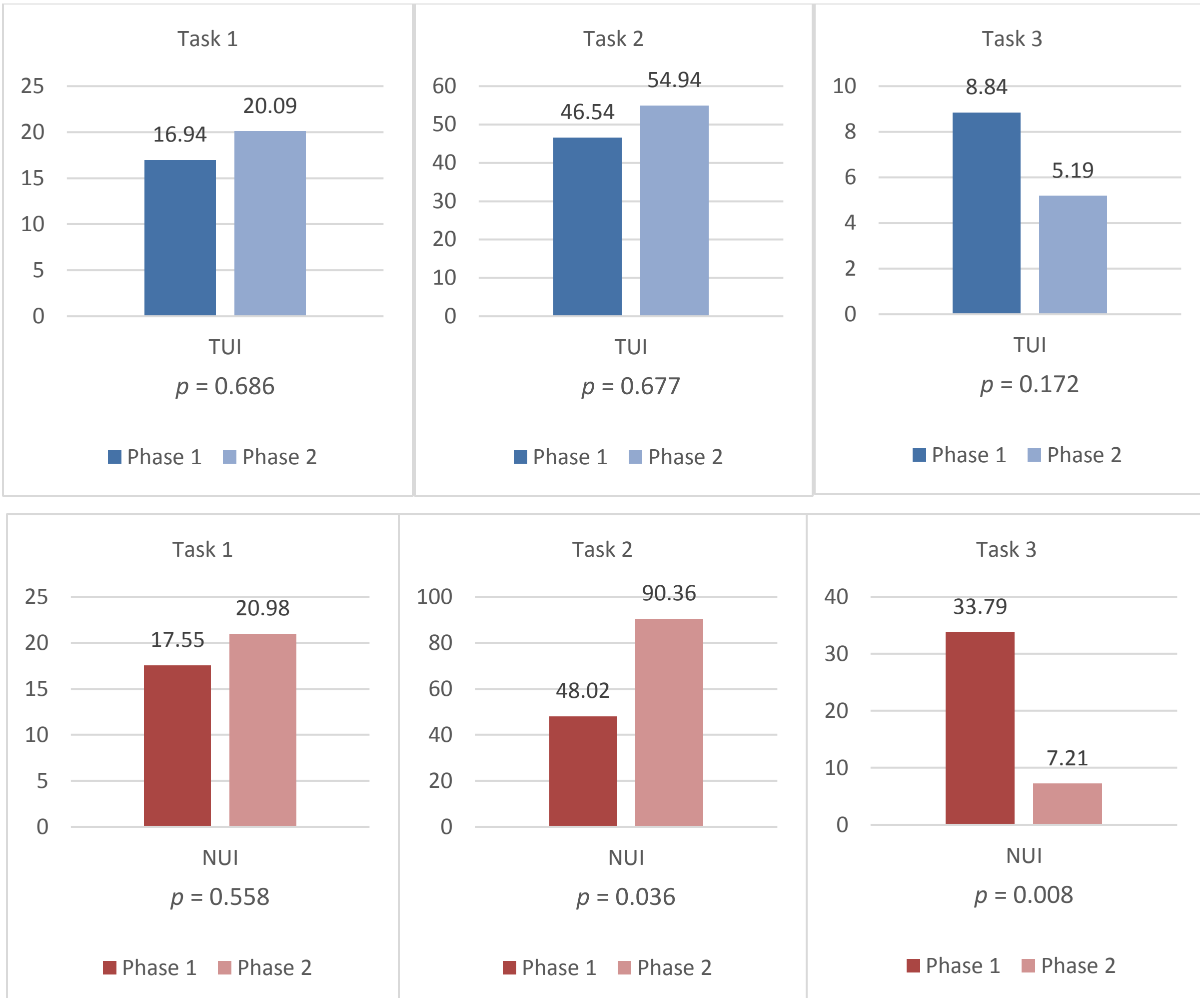

Figure 6.2. Comparing TCT time in Phase 1 with Phase 2 for TUI (blue) and NUI (red).

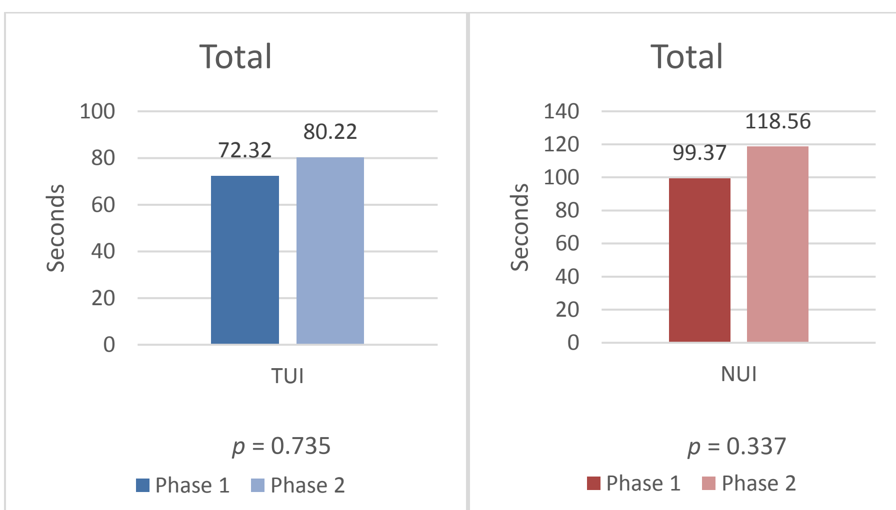

Figure 6.3. Comparing average total TCT time in Phase 1 with Phase 2 for TUI and NUI.

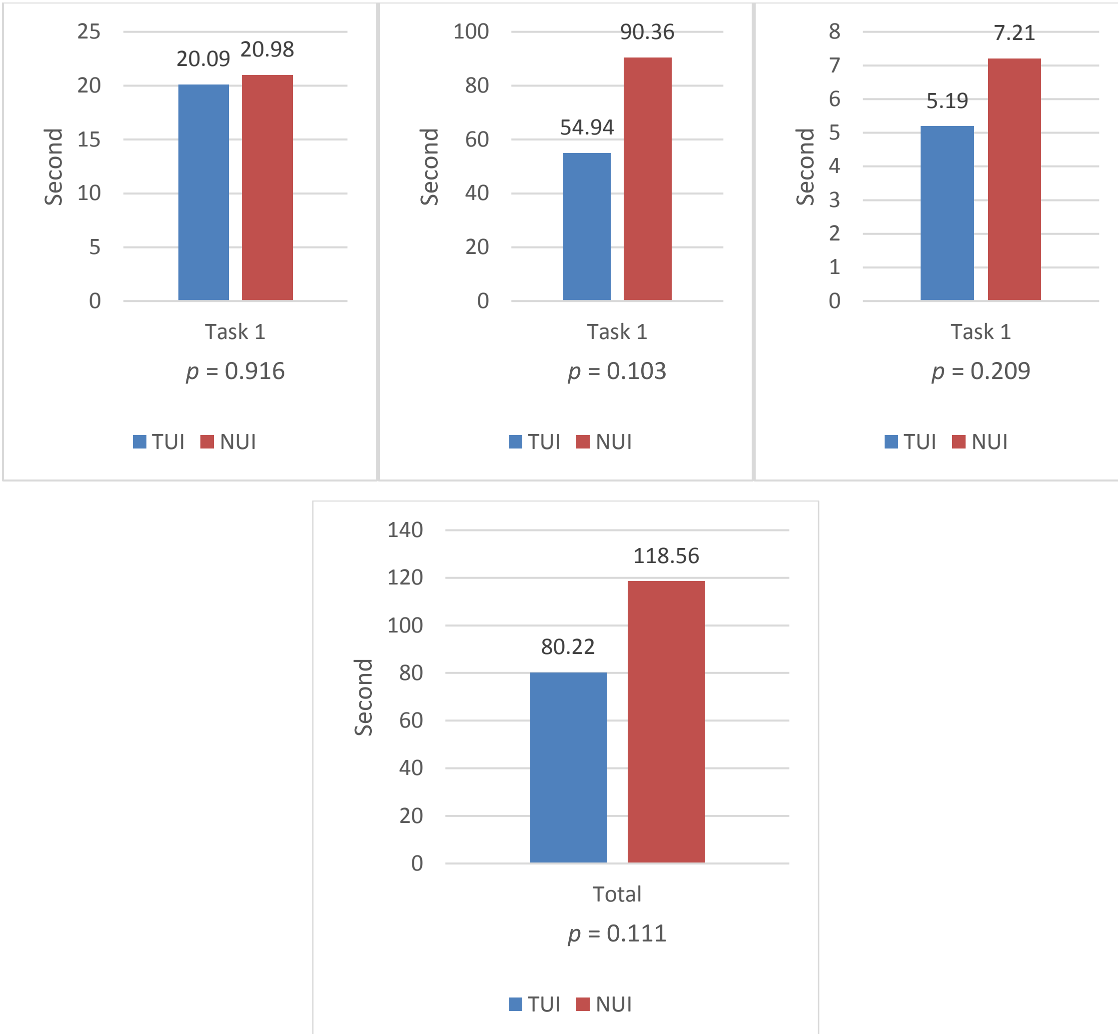

Figure 6.4. Comparing TCT time in Phase 2 for each task.

As shown in Table 6.2 and top row in Figure 6.2, there are no significant differences between the results of phase 1 and phase 2 for TUI. All of the results of t-Test data analysis have p values that are larger than 0.05, with Task 1 $p = 0.686$, Task 2 $p = 0.677$, Task 3 $p = 0.172$, and Task total $p = 0.735$.

It is interesting that in the case for NUI, as shown in Table 6.3 and bottom row of Figure 6.2, there is a significant difference between Phase 1 and Phase 2 for both tasks 2 and 3, with the $p = 0.036$ and $p = 0.008$ respectively.

As shown in Table 6.4 and Figure 6.4, when comparing TCT results from phase 2 of TUI (in blue) and NUI (in red), no clear difference can be deduced. The clear difference of Task 3 TCT where the TUI method is significantly faster than NUI cannot not be observed any longer.

6.6 PHASE 2 DISCUSSION

Recall that Phase 2 reversed the order of testing where users completed Tasks 1 to 3 based on TUI before NUI. Table 6.2 and top row of Figure 6.2 depict that the results from TUI manipulation do not show significant differences. This implies that the TCT for Tasks 1 to 3 for typical users are independent from if they have worked with NUI manipulation before the TUI.

It is interesting that when comparing the Phase 1 and 2 results for NUI, the TCT timing is much more complicated. As shown in Table 6.3 and bottom row of Figure 6.2, while the TCT for Task 1 does not show any significant difference, Task 2 is significantly slower, and yet the TCT for Task 3 is significantly faster. Having significantly different TCT when NUI is tested after TUI suggests that the order of testing to be important for typical users. The inconsistencies in the results, where comparison of the three results leads to three distinct conclusions, suggest that while the order of testing is important, one cannot predict a user's performance for a given test order.

As shown in Table 6.4 and Figure 6.4, while in general TUI continues to show a faster TCT, the statistically significant results of Task 3 and total accumulated time can no longer be observed.

Appendix B shows the data obtained during the user study, there it shows that there is a large variance in the dataset because it has significant outliers in the sample for both NUI and TUI. This might cause the change in Task 3 to not have any significant difference anymore. It was observed that though the testers do not have prior AR head mounted display experience, the ability for the user to complete the tasks seems to be specific to the user's comprehension skills and background understanding of NUI/TUI. In this study, users are not asked whether they have prior NUI/TUI experiences. Some of the users might be very comfortable with the new technology while some might not.

6.7 SUBJECTIVE RATING

Questionnaire data were analyze using the toolkit provided by A. Hinderks et al. [28], shown in Appendix A. The analysis results in numeric values for: attractiveness, perspicuity, and efficiency. The results from TUI and NUI are compared based on the t-Test assuming unequal variances.

6.7.1 *TUI Questionnaire Results*

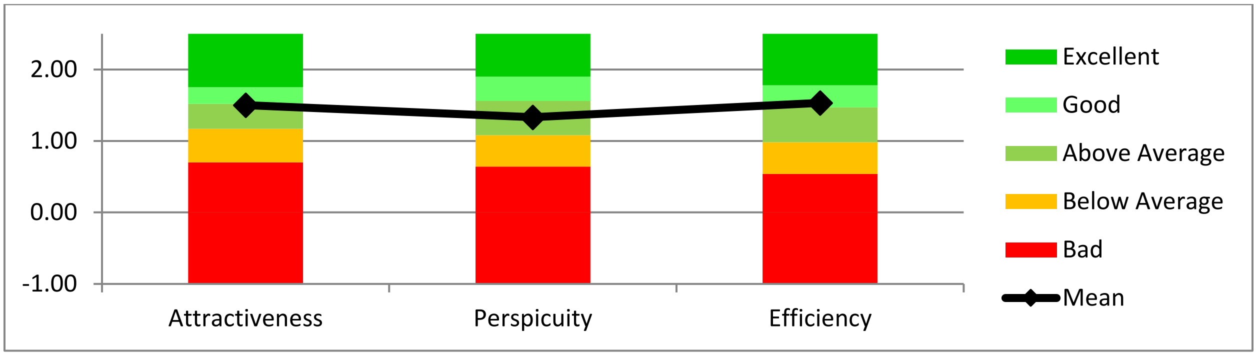

Figure 6.5. TUI Questionnaire result.

The results from the TUI is shown in Figure 6.5. This figure shows that the rating for the attractiveness, perspicuity, and efficiency are all in the range of between “Above Average” and “Good” [28].

6.7.2 *NUI Questionnaire Results*

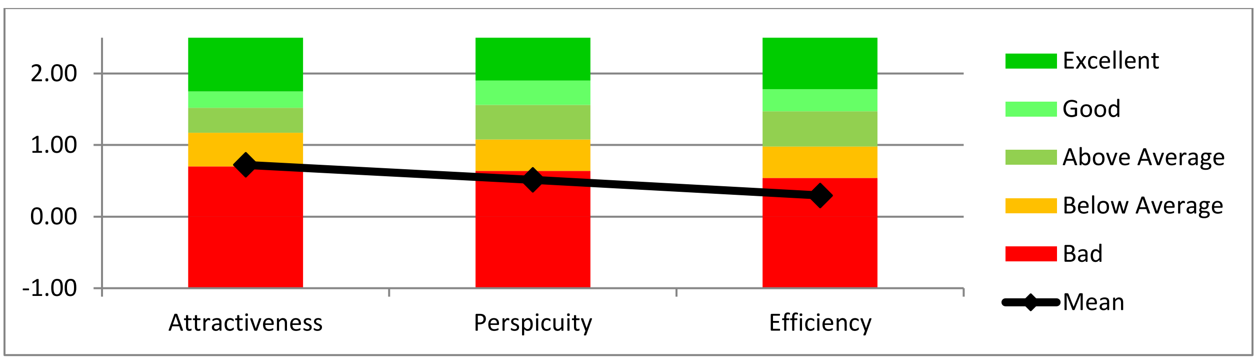

Figure 6.6. NUI Questionnaire result.

The results from the NUI is shown in Figure 6.6. This figure shows that the corresponding ratings are between the ranges of “Below Average” to “Bad”.

6.7.3 *Comparison Between NUI and TUI*

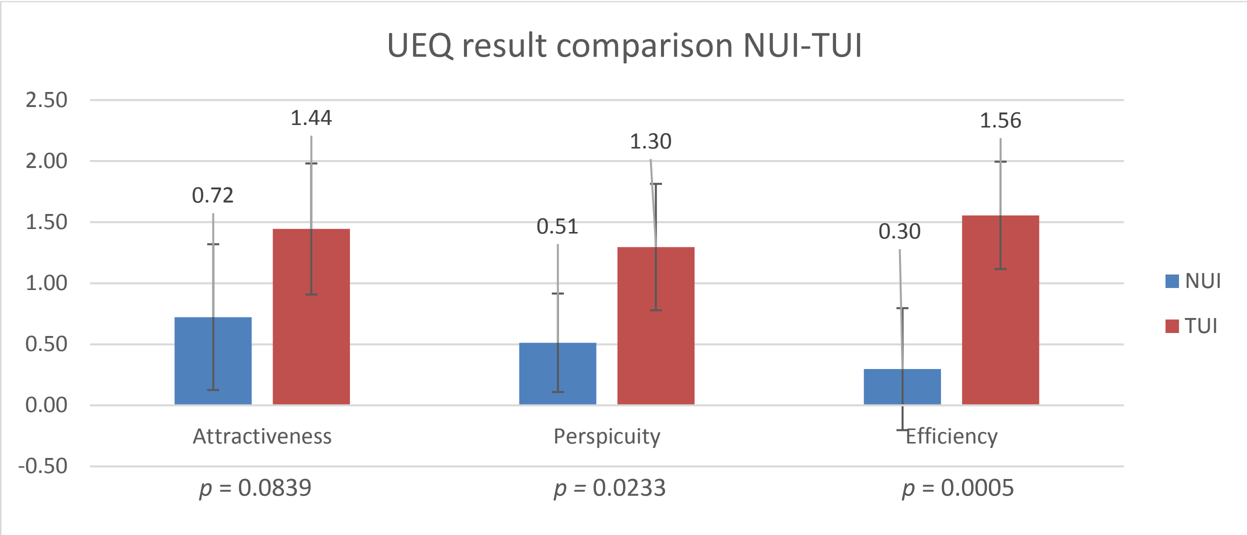

Figure 6.7. Comparison between NUI and TUI.

Figure 6.7 shows the comparison of the two rantings. This figure shows that while the users believe there is no significant difference in "attractiveness," they do perceive TUI to be significantly more "efficient" and "perspicuous".

6.7.4 *Preferred UI Question*

The last question in the UEQ asks the users to choose their preferred controller: the phone controller (TUI) or the built-in gesture (NUI). Table 6.5 shows the user answers to the question where 22 prefer the TUI, four the NUI, and one user who chooses not to answer because the user thought that both of the UI is not practical for doing any tasks.

Table 6.5. Phase 1 and Phase 2 comparison for NUI Results.

	number of users
Prefer TUI	22
Prefer NUI	4
No Answer	1

6.7.5 *UEQ Discussion*

The UEQ results suggest that the users perceive the TUI to be a more efficient way of manipulating virtual objects and easier to learn. This preference may be attributed to the fact that typical users are already well accustomed to using the phone interface for manipulating virtual contents, while most of them might not have any exposure to any kind of NUI. On the other hand, there is no significant difference in attractiveness and between TUI and NUI. The result of the last question where the users prefer TUI more than NUI shows a promising lead on implementation of TUI in head mounted AR. This aligns well with the observation during user study, that many users seem more engaging when handling virtual object using the TUI.

6.8 OBSERVATIONS

Results from observation during user testing: First, left handed people have problems with UI design, because of the button is too far away from their left-hand thumb. Second, most first-time user still did not grasp the concept of AR, this make most user to stand still in one spot, which makes it harder to complete some tasks. Third, most users complain about the narrow fields of view, that it is insufficient to provide the sense of immersion in the AR, and that it makes it difficult for judging distance. Fourth, there is a 3 second delay between built in timer and in hand stop watch timer. Fifth, most users have trouble with TUI rotation control using the provided slider area. This is due to natural finger movement being not completely parallel to the one axis of the touch screens. Finally, for the population of testers, the NUI was not able to recognize many of the voice commands resulting in longer task completion time.

6.9 LIMITATIONS OF THE STUDY

The interface on the TUI is not designed for left handed users because the buttons are aligned to the right-side of the touch screen. This user study only tested a selected group of people with technological background, and with limited number of participants. Nevertheless, it does not change the fact that TUI is generally faster than NUI.

Chapter 7. CONCLUSION & FUTURE WORK

AR and the associated technology with the ability to overlay virtual contents in the physical world are increasingly mature. The advancement of this field brings the interesting research questions of how best to interact with the virtual contents in AR space. With the existing drawbacks of NUI in lack of precision and intuitiveness, this thesis explores the possibility of integrating a tangible user interface device to support virtual object manipulation for head mounted AR display.

This thesis presented results from an initial testing of user interaction using tangible controller in AR environment by trading one free hand available in head mounted AR display for more efficient object manipulation. While limitations exist, the prototype TUI implementation has gone through three iterations of user testing and refinement, and has been observed to be acceptable by our test population. Despite the limitation, the insights gained from analyzing the initial testing results shows that the TUI has a slight edge over simple NUI in efficiency. Additionally, the test results demonstrated another drawback of NUI which is the fatigue observed during user study. These results support the proposed study goals, that the integration of TUI for AR can improve user experience over simple NUI.

In its current state, the TUI implementation is still an initial prototype. The usability of the tangible controller should be continued studied and improved. For example, the widget placements for left-handed users and better widget placements in general. Additional user study and investigation are needed to for more comprehensive and conclusive results. For example, testing with a more general audience, a longer practice time to benchmark user's familiarity, and increase the number of users. Future studies should also focus on other potentially relevant details such as comparison between absolute and incremental manipulation on the TUI controller.

The results from this study contributes to the initial understanding of integrating TUI with head mounted AR. It is demonstrated that users do perceive the TUI solution to be more efficient. This study serves as a starting point for further investigation of TUI solution in AR environment.

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APPENDIX A

PLEASE MAKE YOUR EVALUATION NOW.

For the assessment of the product, please fill out the following questionnaire. The questionnaire consists of pairs of contrasting attributes that may apply to the product. The circles between the attributes represent gradations between the opposites. You can express your agreement with the attributes by ticking the circle that most closely reflects your impression.

Example:

attractive	○	⊗	○	○	○	○	○	unattractive

This response would mean that you rate the application as more attractive than unattractive.

Please decide spontaneously. Don’t think too long about your decision to make sure that you convey your original impression.

Sometimes you may not be completely sure about your agreement with a particular attribute or you may find that the attribute does not apply completely to the particular product. Nevertheless, please tick a circle in every line.

It is your personal opinion that counts. Please remember: there is no wrong or right answer!

Please assess the product now by ticking one circle per line.

	1	2	3	4	5	6	7		
easy to learn	○	○	○	○	○	○	○	difficult to learn	1
fast	○	○	○	○	○	○	○	slow	2
good	○	○	○	○	○	○	○	bad	3
complicated	○	○	○	○	○	○	○	easy	4
unpleasant	○	○	○	○	○	○	○	pleasant	5
inefficient	○	○	○	○	○	○	○	efficient	6
impractical	○	○	○	○	○	○	○	practical	7
clear	○	○	○	○	○	○	○	confusing	8

Which Type of Interface Do you Prefer?

a. Phone Controller b. Built-in Gesture

APPENDIX B

Phase 1 data NUI

Subject #	NUI							
	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7	Total Time
1	7.05	50.01	10.2	5	19.8	105	220	417.06
2	6	15	130	30	90	48	100	419
3	14	12	66	11	63	148	160	474
4	49	13	53	8	168	32	121	444
5	10	9	57	14	60	177	40	367
6	40	92	10	6	16	111	100	375
7	20	16	23	8	16	69	53	205
8	30	14	30	10	45	150	33	312
9	5.1	146.7	8	8.9	19.5	60.2	38	286.4
10	6.66	31.77	11.8	20	15.6	13.6	59	158.43
11	8.55	4.3	10.15	15.75	109	142	79	368.75
12	27.9	179.348	34	8	43	130	87	509.248
13	15.81	49	9.1	4.05	57.68	67	32	234.64
14	13.2	17	46.7	7.46	15.2	121	33.6	254.16
15	10	71.3	7.9	12.4	12.3	39.9	31.78	185.58
Average	17.551	48.029	33.790	11.237	50.005	94.247	79.159	334.018
STD Dev	12.931	51.590	32.258	6.475	42.722	48.667	52.944	106.146

Phase 1 data TUI

Subject #	TUI							
	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6	Task 7	Total Time
1	2.5	4.1	8.2	5.2	16	90	97	223
2	8	22	32	5	112	95	94	368
3	7	4	5	3.4	46	50	90	205.4
4	20	11	10	13	90	170	45	359
5	12	5	2	5	12	71	75	182
6	43	60	12	12.68	11.09	117	30.87	286.64
7	15	26	2	4	16	27	37	127
8	14	60	12	30	87	169	22	394
9	24.25	11.9	1.69	5.48	17.7	76	30.1	167.12
10	21.9	128.1	22.5	7	73	20.51	80.9	353.91
11	10.1	118	2.56	7	39	226	50	452.66
12	34.02	130.55	6.4	17.41	24.5	153.8	114.8	481.48
13	12.18	60.34	1.09	5.94	46.75	38.78	22.71	187.79
14	21.11	37.26	12.02	10.83	41.38	47.68	20.57	190.85
15	9.06	19.91	3.13	4.58	23.81	18.54	23.25	102.28
Average	16.941	46.544	8.839	9.101	43.749	91.354	55.547	272.075
STD Dev	10.428	43.960	8.376	6.814	31.227	61.324	31.758	116.778

Phase 2 data TUI and NUI

Subject #	NUI				TUI			
	Task 1	Task 2	Task 3	Total Time	Task 1	Task 2	Task 3	Total Time
1	21.81	37.8	11.8	71.41	12.84	34.6	5.42	52.86
2	19.2	173	8.61	200.81	91	74.72	2.3	168.02
3	21.59	82.23	7.72	111.54	21.68	217.15	3.39	242.22
4	29.14	141.44	7.82	178.4	10.35	10.65	2.79	23.79
5	52.05	122.78	7.89	182.72	4.57	48.24	2.86	55.67
6	49.19	31.6	9.12	89.91	11.44	57	9.59	78.03
7	2.29	105.34	3.79	111.42	2.66	34.53	1.49	38.68
8	9.42	48.45	1.78	59.65	6.72	8.15	12.18	27.05
9	3.781	127.91	4.59	136.281	12.95	72.83	1.2	86.98
10	15.11	65.37	10.957	91.437	17.98	46.26	1.99	66.23
11	7.79	102.79	7.52	118.1	41.83	42.33	4.363	88.523
12	20.5	45.6	4.9	71	7.06	12.8	14.73	34.59
Average	20.989	90.359	7.208	118.557	20.090	54.938	5.192	80.220
STD Dev	15.328	43.727	2.818	45.082	23.584	53.279	4.307	61.535