OBJECT MANIPULATION TECHNIQUE DEVELOPMENT AND EVALUATION IN DESKTOP VIRTUAL ENVIRONMENT

by

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ABSTRACT

JINBO FENG. Object manipulation technique development and evaluation in desktop virtual environment
(Under the direction of Dr. ZACHARY WARTELL)

Object manipulation is one of the major operations in 3D graphical interaction. For existing high degree-of-freedom (DOF) manipulation techniques, most of them have shown to be more efficient or intuitive in their specific experiments. However, these experiments often ignored essential factors within practical usages. Such factors include accuracy, the variation in required precision, the duration of usage, etc. These reasons may partially explain that many experimentally successful 3D interaction techniques are still not widely used in the marketplace.

Based on previous experimental conditions and conclusions, I designed a series of manipulation techniques and corresponding experiments in order to develop manipulation techniques which are more intuitive/flexible than conventional methods that dominate the marketplace and also more suitable for longer duration usage with better precise control than existing typical techniques based on high DOF input devices.

I started my research from two extremes (low DOF input devices - high DOF input devices) and try to find a middle optimum location between the two which benefits advantages from the two extremes. I have developed two sets of object manipulation techniques for desktop environment. The first set is based on high DOF input devices, experimental evaluations revealed the advantages of bimanual controls; scaling down to match had faster completion times than scaling up operations; users preferred One-Handed with Two-Hand Scaling than Spindle+Wheel technique. The second set of object

manipulation techniques contains three desktop based input devices. The result showed users preferred separated rotation and translation isotonic position control than the integrated pose (translation + rotation) control with isometric rate input. The data analysis also proved the technique with isotonic position control outperformed the technique with isometric rate control in the final control phase of the docking test. Besides, the final consecutive experiments investigated users' inclination about DOF separation and integration in different phases of the manipulation based on isotonic position control. The results revealed the advantage of integral control of translation with rotation and the benefit of separate control between pose and scaling.

The data analysis and qualitative summary from variations in hardware/software components and fundamental DOF control investigation showed guidelines for future development which could inform the design of further object manipulation techniques to improve efficiency and practical usage.

DEDICATION

This dissertation is dedicated to Dad, Mom, Grandfathers (Mingguo Feng, Dacheng Tao).

ACKNOWLEDGMENTS

I am very grateful to Dr. Zachary Wartell for advising me through my PhD study. I deeply appreciate the valuable suggestions from my committee members, Dr. Aidong Lu, Dr. Min Shin, Dr. Paula Goolkasian and Dr. Isaac Cho. Also appreciate suggestion from Dr. Celine Latulipe. Appreciations are expressed to the Graduate and Professional Student Government (GPSG) at UNC Charlotte for financial supports to my study.

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NOMENCLATURE

eta^2	effect size
M	sample mean
SD	standard deviation
p-value	significance level of the test
SE	standard error
m_Metric	metric for evaluating allocation of control
SOC	Simultaneity of control (SOC)
EFF	Efficiency of Control
DOF	Degree of Freedom

LIST OF ABBREVIATIONS

Pose	3DOF Translation + 3DOF Rotation
OH	One-Handed Manipulation
OTS	One-Handed with Two-Hand Scaling
S+W	Spindle+Wheel
TM	Trackball + Mouse
KM	Keyboard + Mouse
3M	Spacemouse Technique
OHS	One-Handed with Separate Translation and Rotation
OHISS	Pose + Separable Scaling
OHIS	Pose + Integrated Scaling
OHSS	Pose + Separated Scaling

CHAPTER 1: INTRODUCTION

1.1 Human Computer Interaction

Human–computer interaction (HCI) researches the design and use of computer technology, focusing particularly on the interfaces between people (users) and computers. The HCI tasks could be work, play, learning, communicating, etc. The goal of HCI is to allow the users to carry out tasks safely, effectively, efficiently, enjoyably, etc. The usability of a HCI system often contains the combination of Ease of learning, High speed of user task performance, Low user error rate, Subjective user satisfaction, User retention over time and Usefulness/Completeness [1].

There are many types of interaction such as mouse cursor icon menu (WIMP) (Figure 1.1), pen computing, touch input, Gesture/Body input, etc. The WIMP is the predominant interface paradigm which has been widely used in daily life for decades. After all, a lot of the workaday world with which we deal is flat—not just our Web pages but our documents, presentations, and spreadsheets too. Most of them belong to 2D interaction [2]; Pen computing is a user-interface using a pen (stylus) which is generally used to press upon a graphics tablet or touchscreen, as opposed to using a more traditional interface such as a keyboard, mouse or touchpad; Touch inputs are widely used in tablets, mobile phones with touchscreens (Soft Keyboard); Gesture/Body input includes Wii, Kinect and other specialized hardware for tracking.

Figure 1.1: Typical inputs: WIMP (A), Wacom bamboo (B), touchscreen (C), Wii Remote Controller (D)

1.2 Virtual Environment and 3D User Interfaces

Virtual environment is typically a 3D environment which simulates real world. It is applied to areas such as aerospace and automotive, and equally large and even more important activities in the life-saving and life-giving pharmaceutical and health care industries (Figure 1.2). In many cases, these environments require users to provide some input and respond to these inputs which is of 3D interaction.

This thesis focuses on interactions based on desktop VR system. A desktop VR system offers an affordable solution that displays a virtual environment on a conventional desktop PC in a non-immersive manner [3]. Comparing with donning a helmet and data glove, the input devices such as a mouse and the usage of a desktop PC provide a more convenient and easy to follow interface for the engineers indeed. Thus, alternatively, in many VR applications, users prefer a desktop virtual environment due to its low cost and portability.

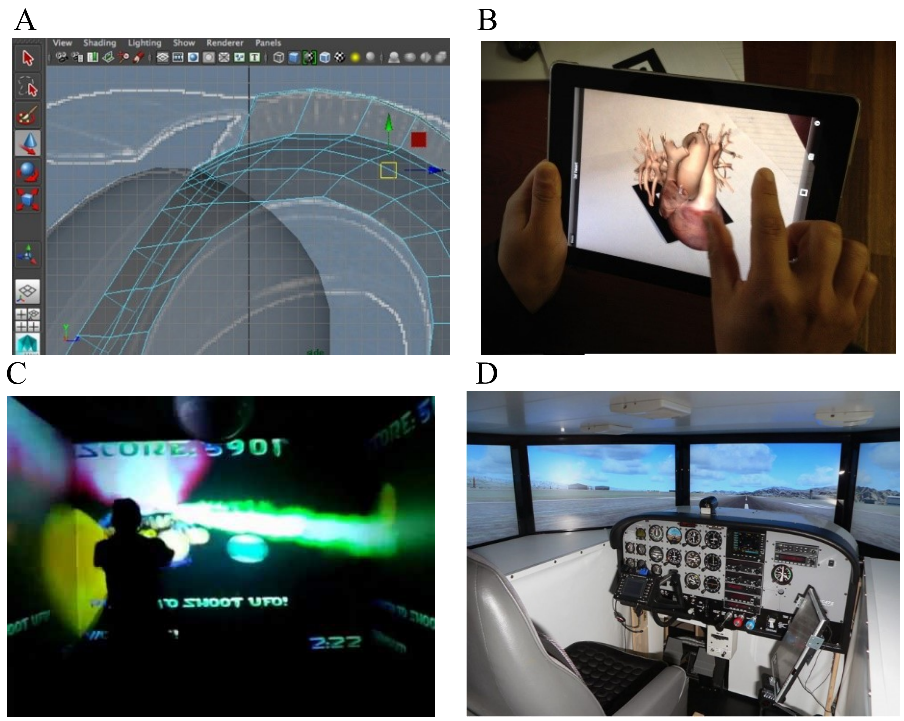

Figure 1.2: 3D Modeling in Maya (A), Medical inspection (B), Flight simulation (C), Stereo game in the Cave (D)

Interaction is not defined by an input device alone, but by the combination of a device and an interaction technique [4]. For instance, in 3D object rotation, the mouse is typically used with the virtual sphere technique [5], while a 6 degree-of-freedom (DOF) device is used with direct mapping (either absolute or relative) [6]. Thus, the combination is that different device be associated with its most suitable interaction technique in making performance comparisons, rather than choosing a single interaction technique for all devices.

Basically, the 3D interaction includes placement, rotation, pointing and scaling etc. These interactions could be divided into two different clusters: camera manipulation and Object manipulation. Camera manipulation is to apply interaction techniques to change the camera location and orientation or even view angle. Object manipulation basically involve object selection, changing the location, orientation and size of the virtual object in the environment. This proposal only focus on object manipulation.

1.3 Object Manipulation

Object manipulation is the manipulation of an object in the virtual environment. Typically it has to deal with multi degrees of freedom (DOF), such as xyz translation, xyz rotation and scaling. Many computer applications require virtual three dimensional object manipulations, such as architectural modeling, virtual model exploration, engineering component design and assembly among others. Object manipulation also contains two parts: 3D user interface input hardware and 3D interaction techniques [2]. The input hardware could have high DOFs or low DOFs. Basically, a 6DOF input device could control 3DOF translation and 3DOF rotation of the target with each of its DOF control assigned separately. Also, for the corresponding software component of the interaction technique, a direct mapping between the physical and virtual movement could be possible, which means the virtual object moves exactly as the user's movement controls as input. A low DOF input device as lesser DOFs than the DOFs to be controlled in the virtual space. For instance, in a 3D placement task, there is presently no way to perform this task directly with a regular mouse. The standard solution is to decompose the task into two 2D placements, e.g., one in the x-y plane, and a second in the x-z plane [4].

1.4 Current Issues of Object Manipulation

Many current applications with commercial 3D display systems, such as Nvidia 3D Vision, use the traditional mouse and keyboard as user input devices. One of the disadvantages is that their movements are restricted into the 2D desk plane and therefore not intuitive for 3D object manipulation. Although input devices which allow manipulation movement in 3D space such as flying mouse are more natural [7] and efficient for the user to connect the movement information between the real world and the virtual environment, there are many disadvantages such as fatigue and Difficulty of device acquisition [7], which means it's difficult for common users to get these devices.

1.5 Research Methodology

In the case of 3D interfaces, however, there is still not an obvious winner suitable for all applications [7], and it is not easy to combine all advantages of high DOF input devices with conventional 2D input devices. We attempt to merge the intuitiveness and efficiency of 3D input devices with conventional devices which hold precision and less fatigue features in order to maximize the overall practical ratings of the interaction technique.

Investigation and research basically started from two extremes (from low DOF input devices and from high DOF input devices) and try to find a middle optimum location between the two which has the benefits from each of the two extremes.

In this thesis, a pragmatic approach is chosen to find out principles and methods to create efficient, intuitive and practical manipulation techniques. Object manipulation techniques are designed and implemented with different hardware combinations or interaction software component improvements. Experiments are then carried out for representative tasks. Conclusions and discussions are drawn based on quantitative and qualitative analysis from the user studies.

CHAPTER 2: BACKGROUND

2.1 Definition and Conceptual Classification of Input Techniques

Zhai classified the input devices into two categories [8]: isometric devices (they offer resistance and stay put while you exert force on them) and isotonic devices (they offer no significant resistance and are used to track users as they move around the virtual world).

A B

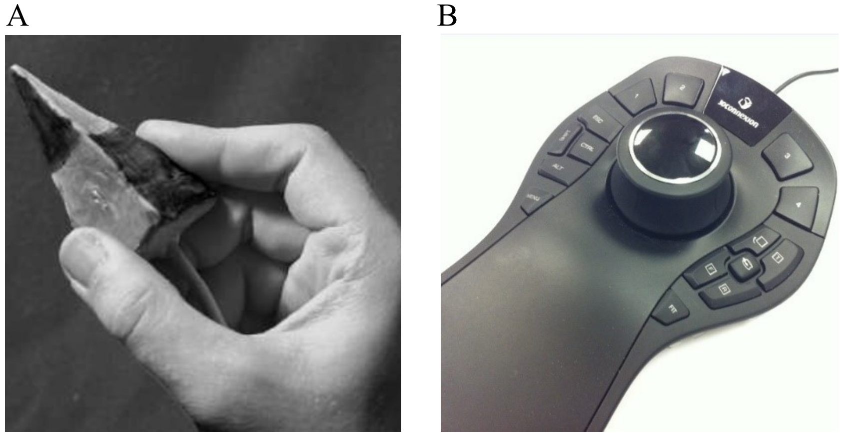

Figure 2.1 The Fastrak receiver enclosed within "Crayola Model Magic" modeling material, shaped and coloured to resemble the virtual pointer [9] (A). The Spacemouse Pro (B)

Free-moving (free space) 6DOF position-control devices is of isotonic input which allow the physical movements to be mapped directly to virtual 3D object movements which provide intuitive and efficient operation [7] [10]. Some researchers also use Polhemus FastrakTM motion tracking which has precise 6DOF tracking and little latency as the basis for their modified 6DOF input devices [9] [11]. The

Spacemouse [12] (Figure 2.1 B) is designed for CAD users which allow the user's hand to rest on the desk and control the controller cap on top of the base. The cap enclosed a 3Dconnexion 6-Degrees-of-Freedom (6DOF) sensor which detect the force in various directions applied to it.

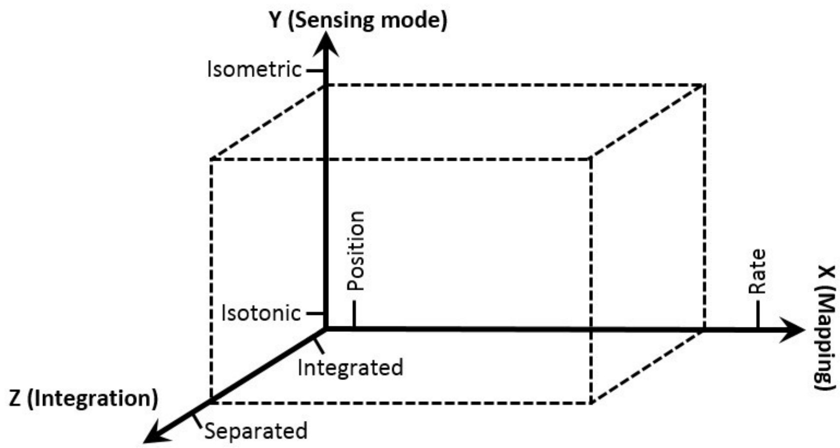

Figure 2.2 A framework for manipulation schemes [13]. This figure is reproduced without the authors' permission.

The X axis in Figure 2.2 defines a continuum of different mapping relationships between the user's movement (hand, limb) and the resulting movement of an object being manipulated, including translation, rotation, etc. Near the origin of the X axis is where the output of the user's limb is mapped to object position or orientation by a pure gain. This is often referred to as position control. At the outward end of the X axis is where the transfer function is a first order time integration, or often referred to as rate or velocity control.

The third dimension, Z axis in Figure 2.2, is the degree of control integration. The origin here represents fully integrated control (for instance: 3DOF translation + 3DOF rotation + 1 DOF scaling), while the other extreme represents completely separated control (for instance: seven 1DOF controllers). Between the extremes of the Z axis could be the options of two 3DOF controllers, one for rotations and one for translations, which is the way that some tele-robots are controlled [8].

2.2 User Centered Design Process

Each chapter of this thesis basically follows user-centered design, a philosophy based on the needs and interests of the user, with an emphasis on making products usable and understandable [1]. The basic user-centered design process is as follows [14]:

1. Understand constraints/context

2. User analysis

3. Task analysis

4. Function allocation (between human(s) and computer)

5. Define usability criteria

6. Design UI (Use low-fidelity prototyping)

7. Build & test high fidelity prototypes (Apply formative / summative evaluation techniques & iterate)

8. Build & test the real application. (Apply summative evaluation techniques & iterate)

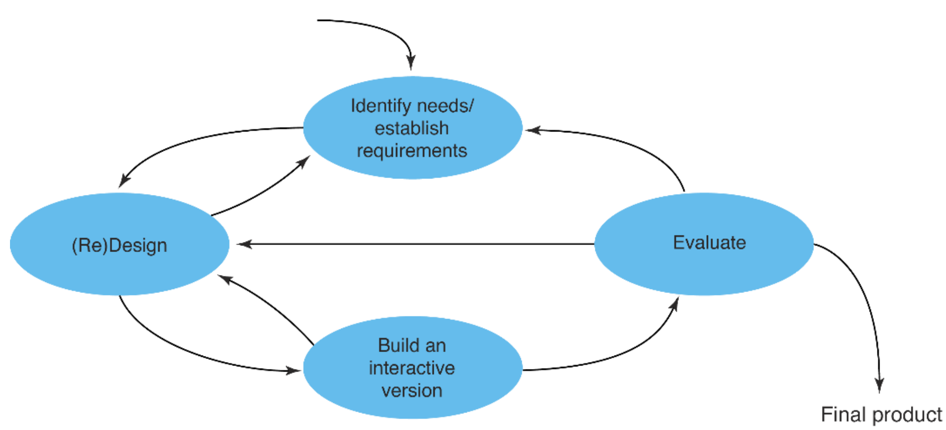

Figure 2.3 A user- centered design process [14]. Figure used without author's permission

2.3 Evaluation Methods

For the evaluation, there are some commonly used methods in the field of HCI such as: Formal (Experiments) user studies, Observation & Think-aloud, Predictive Evaluation (Fitt's law, Hick's, Key-Stroke Level Model), Wizard-of-Oz, Discount Usability Evaluation (Heuristic Evaluation, Cognitive Walkthrough), Diary Studies and Experience Sampling, etc. This thesis basically chose the formal user study for the evaluation of the manipulation techniques because of time constraint and effectiveness for analysis.

Form of results obtained are quantitative and qualitative separately. The quantitative results are basically obtained from program recording during the user study and is used for inferential statistical analysis. The qualitative results come from users' feedback in the form of pre/post questionnaires.

CHAPTER 3: STEREO DESKTOP VR AND INTERACTION TECHNIQUES

In this chapter, we will demonstrate and evaluate several free space (based on isotonic 6DOF input devices) manipulation techniques published to SUI 2015 [15] and try to find out efficient and intuitive methods for this kind of input devices. Furthermore, we tried to understand the fundamental reason for both advantages and disadvantages of these devices and corresponding manipulation techniques demonstrated during the experiment.

For this experiment, we chose Polhemus Fastrak™, the sensor of which could be used as an isotonic 6 degree of freedom (DOF) input device. The electromagnetic motion tracking system has little sensing time lag and tracking loss issue.

3.1. Introduction

Many interaction techniques have been developed for 3D manipulation and navigation [2]. Among others, these involve single and bi-manual 2D input devices, multi-touch, 6DOF isotonic tracked held devices (or "props") and 3D tracked hands and fingers using various technologies. Common 3D interactions are 6DOF manipulation and navigation. However, 7DOF interaction is important as well. For object manipulation this means including scale.

For 3D user interfaces, besides the various application requirements that influence the choice of input devices, a key issue is the mapping from the input devices DOFs to the manipulated 3d DOFs. Depending on the device technology and mapping design, this might allow all 7DOFs to be manipulated simultaneously or in various subset combinations. In a docking task, the user must align a target 3D object with an objective object [8]. A common object shape is a tetrahedron. In 6DOF docking the target and object are the same size, while in the 7DOF docking they differ in size.

For a 6DOF task Masliah et al. [16] find that users tend to allocate their control to the rotational and translational DOFs separately and switch control between the two groups. With training, allocation of control within the translational and rotational subsets increases at a faster rate than across all 6 DOFs together. Their results suggest that the simultaneous manipulation of all DOF does not necessary lead to the best performances.

We evaluated 3 input techniques using isotonic 6DOF devices for a 7DOF manipulation task. Our goal is to explore the effects of separation versus simulateaneity of the Euclidean DOFs (xyz,yaw,pitch,roll) and Scale. Our study is performed in a stereo Fish Tank VR [17] (Desktop VR [18]) environment with precision-grasped, 6DOF button balls. We performed a user study with 12 participants comparing the performance among the 3 following techniques:

- One-Hand+Scale [17] [19] – an unimanual, separated 6DOF+Scale technique
- Spindle+Wheel [20] – a bi-manual, simultaneous 7DOF technique
- Grab-and-Scale [21] – a bi-manual, separated 6DOF+Scale technique. (Note we use a trivial variant of the original [21]).

Our choice of these 3 techniques is discussed in Section 2.

The study's manipulation tasks include conditions that both require and do not require scale adjustment. Overall, we find that when users do not have to scale, all three techniques performed equivalently. If users have to scale, Spindle+Wheel and Grab-and-

Scale perform similarly, but both are better than One-Hand+Scale. Some of these results are consistent with our detailed hypothesis and prior related work [22] [20] [23]; others are not.

3.2. Introduction 7DOF Object Manipulation

7DOF control is essential for virtual object location (x,y,z), orientation (yaw, roll, pitch) and scale. It is also important in multi-scale virtual environments where the view scale factor is discernible as a 7DOF degree-of-freedom due to stereo parallax, head-coupled display's motion parallax and direct 3D manipulation [24] [25].

Our study evaluates three 7DOF manipulation techniques. We choose a 7DOF object manipulation task rather than a 7DOF travel task. Therefore, our virtual environment contains target objects with different sizes that the user must "dock" [8] with a docking object. Our choice of particular techniques for comparison is based on our desire to compare uni-manual versus bi-manual and compare simultaneous 7DOF manipulation versus separated 6DOF+Scale manipulation.

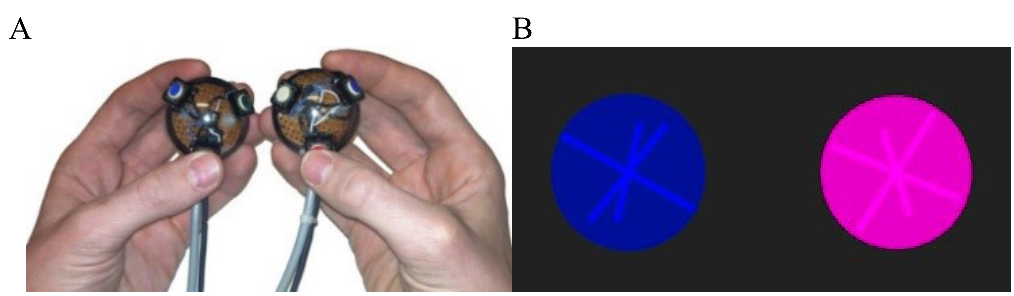

Figure 3.1 Button balls (A) and corresponding spherical cursors (B); left cursor is blue and right is pink [20] ("Reproduced with permission").

For all 3 techniques, the user uses 6DOF tracked buttonballs (isotonic input) [26] [8] [27] (Figure 3.1 A). The Fish-tank VR display shows one or two spherical cursor (Figure 3.1 B). The translation and rotation gain factors are 1. The user sits with his torso roughly 1 meter from the display. At the start of a session the user holds the button balls and rest her elbows on the chair's arms and the experimenter sets a translational offset that places the 3D cursors in the center of the screen [26]. This is designed to maximize the degree to which the user rests her elbows during interaction. The user's task is to select target boxes of varying sizes and manipulate them to dock (i.e. match) the size and pose of a fixed objective box (Figure 3.2). Like colored faces must be matched, so this is a 7DOF task.

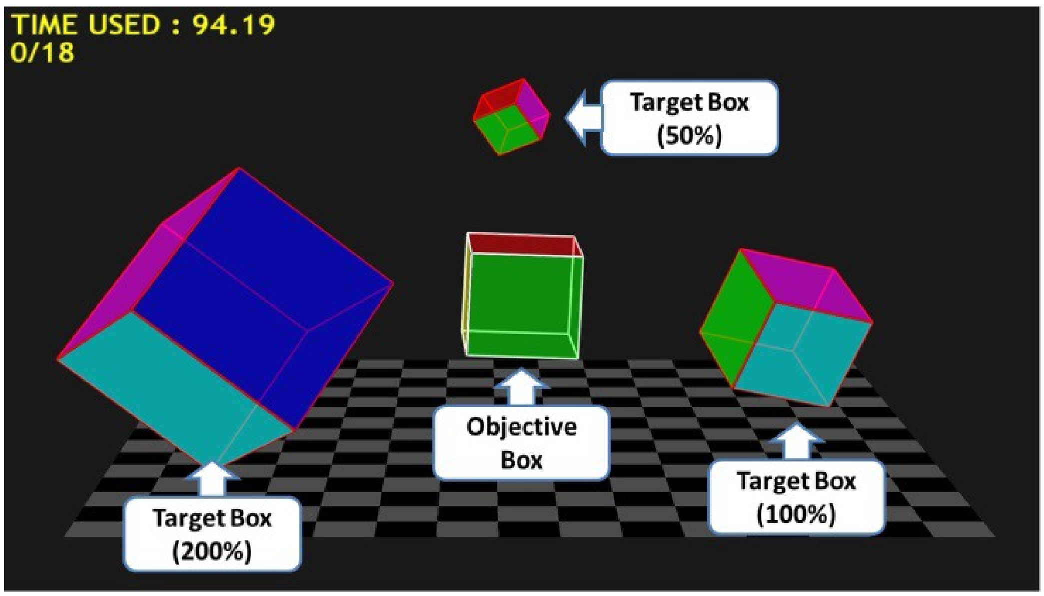

Figure 3.2 Screen capture of virtual environment displayed on desktop VR system in the experiment. The white frame objective box locates in the screen center with red frame target boxes around

To simplify exposition, this document assumes the user is right hand. In all our actually interfaces and user studies the roles of the cursors are reversed for left hand dominant users.

3.3. One-Handed Manipulation (OH)

The One-Handed manipulation technique (OH) works as follows. For translation and rotation, the user presses and holds the selection button after placing the cursor inside the target box [17] [19]. Then the box movement has been attached to the cursor and with the cursor center as the rotation center. To scale the target box, the user places the cursor inside the box and presses and holds a second scaling button. To scale up and down, the user moves the cursor hand toward or away from the screen. Scaling is controlled by rate control. Prior work suggests for this one-hand 7DOF technique users prefer to control scale with rate control rather than position control [20].

3.4. Spindle + Wheel (S+W)

Our experiment's first two-handed manipulation condition is Spindle+Wheel [20]. Spindle+Wheel extends prior work [22] [21] [28] by allowing all 7DOF to be manipulated simultaneously.

A

B

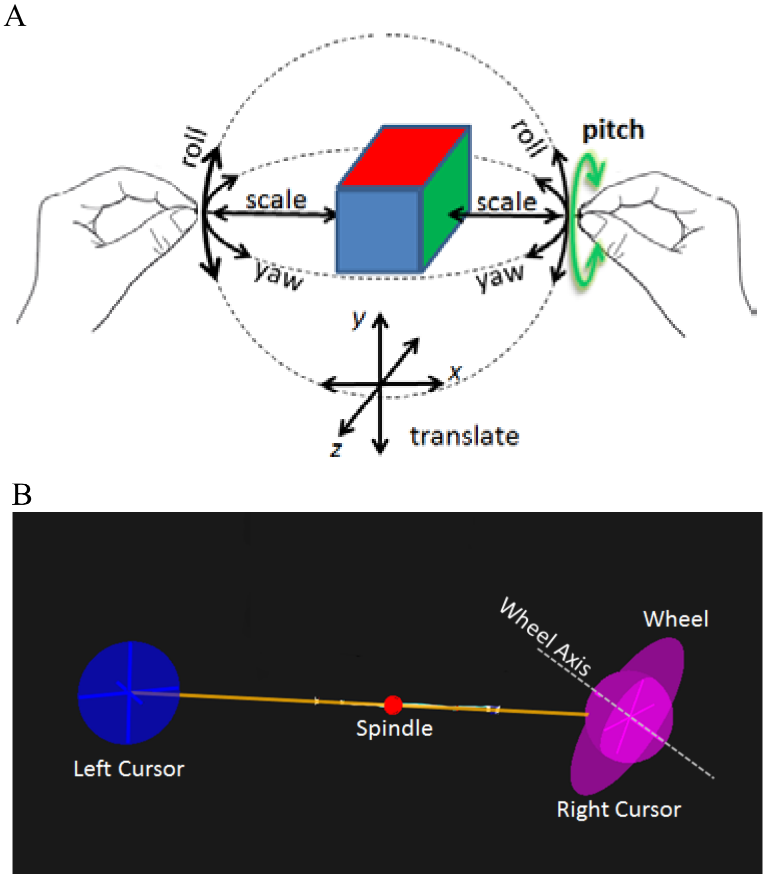

Figure 3.3 Two-Handed condition. (A) Bimanual DOF's of Mapes and Moshell "5DOF+Scale" technique [22] versus "Spindle+Wheel" [20] which adds pitch (green). (B) Spindle+Wheel Visual feedback ("Reproduced with permission").

A thin orange cylinder, the “spindle”, is drawn between the two cursors [28] with a small red sphere at the mid-point. The “wheel” [20] is a disc on the right cursor indicating the plane of rotation for the pitch rotation (Figure 3.3 B).

To select an object, the user places the spindle’s center inside the target object and presses and holds the select button on the left button ball. This engages object manipulation [28]. Rotating one hand about the other while keeping their distance constant, rotates the selected box in yaw and roll, moving the hands closer or farther apart scales the box, while translating the hands rigidly translates the object [22]. Figure 3.3 A (ignoring the pitch) is Mapes and Moshell’s 5DOF+Scale bimanual technique. Spinning or twisting the right button ball with the fingers around wheel axis rotates the selected object around the spindle axis (“pitch” in Figure 3.3 A) [20]. Cho et al. demonstrate that Spindle+Wheel yields faster completion times than Spindle for a 7DOF docking task implemented as multi-scale travel [20].

Song et al. [29] present a free-hand “Handle-Bar”; by our observation Handle-bar replicates 5DOF+Scale [22] with nearly identical visual feedback of Spindle [28]. Song et al. do not comment on the replication. Mendes et al. [23] present “Air TRS”. By our observation, Air TRS replicates 5DOF+Scale swapping in newer tracking technology (Kinect free-hand tracking replacing tracked pinch gloves). Mendes et al. [23] do not remark on this. By our observation, the only difference between Handle-bar and Air TRS is that in Handle-bar the selection point in the Handle-bar (aka Spindle) mid-point (as done prior in Spindle [28]); while Air TRS the selection point is the pinch point of hand that initiates the interaction (as done previously in [22]). Otherwise, the bi-manual DOF mappings replicate 5DOF+Scale [22] with different input devices

3.5. One-Handed with Two-Handed Scaling (OTS)

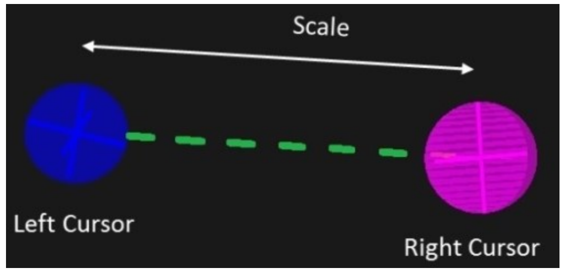

Figure 3.4 Graphical representation in scaling manipulation [20] ("Reproduced with permission").

The next technique is called "One-Handed with Two-Handed Scaling" or OTS. The DOF mapping of OTS is the same a Culter et al.'s bi-manual "Grab-and-Scale". However, Grab-and-Scale is implemented using tracked pinch gloves (and no user study was performed). In OTS, the left hand button ball operates the same as the OH technique for translation and rotation by pressing a left cursor button. Additionally, pressing a right cursor button engages scaling. A dotted green line between the two cursors appears in scale-mode (Figure 3.4). The scale is adjusted based on any ensuing change in distance between the cursors; this is similar to the Spindle+Wheel technique.

The DOF mapping of OTS is the same as Culter et al.'s bi-manual "Grab-and-Scale" (Table 1, row 4), but Grab-and-Scale uses tracked pinch gloves while OTS uses buttonballs. Also, unlike Grab-and-Scale, OTS also includes the deliberate translation offset between input device and cursor to counter fatigue [26]. OTS also essentially uses the same 7DOF mapping as the Hand-in-Middle (HIM) technique [27] and uses equivalent input devices, however, the target task differs.

We compared and contrasted our study's results to Mendes et al.'s [23] user study. So we briefly review their techniques and relate them to the ones we evaluate. Mendes et al. [23] present a bimanual free-hand technique called "6-DOF Hand". By our observation, 6-DOF Hand is the same as Grab-and-Scale but uses free hand tracking instead of tracked gloves. Hence, 6-DOF Hand and OTS differ in that OTS has an offset and uses buttonballs and two buttons, while 6-DOF-Hand is free-hand with two pinch gestures but no offset.

Mendes et al. [23] also present “Air TRS”. Like 5DOF+Scale, Air TRS controls 5+1 DOF’s, xyz-yaw-roll+scale, but while 5DOF+Scale is symmetric, Air TRS is asymmetric. In particular the center of scale and rotation is always the left hand. Air TRS appears to be a hybrid of 5DOF+Scale and Grab-and-Scale.

Mendes et al. also present 3DOF-Hand. It provides simultaneous 7DOF. Scaling works as in 5DOF+Scale. Translation is controlled by the initiating (left) hand but rotation is controlled by mapping the secondary hand’s orientation directly to the selected object (rotation gain is 1).

3.6. Experiment

The system is a stereoscopic, Fish-tank VR setup. It uses the Nvidia 3D Vision with Nvidia Quadro 2000 and a 120Hz 22” LCD monitor. The position of button balls and user’s head are tracked by a Polhemus Fastrak. Software is written in OpenSceneGraph and our VR plugin.

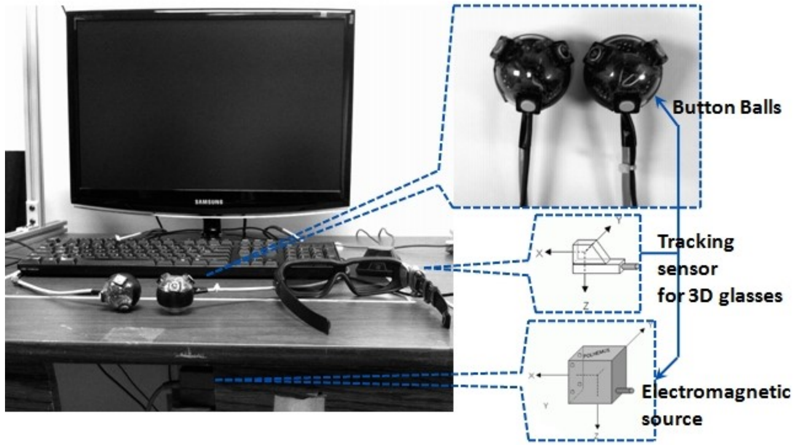

Figure 3.5 Desktop VR hardware configuration

The virtual environment has a checker-board ground-plane (Figure 3.2). It is 40 cm square with half appearing behind the display surface and half appearing in front. In the center of the screen is a translucent box, the Objective Box, of fixed size and at a random orientation per trial. Each face has a different color. This cube's pose remains stationary relative to the display screen during target box manipulation. At each trial, three target cubes boxes with 50%, 100% and 200% of the objective box's size appear at random locations and orientations on the ground-plane. The user must select the target boxes one by one and align the target cube with the objective cube. This requires object rotation, translation, and scaling to match the sizes.

When the distance between the target cube's corresponding vertices is within a tolerance (0.84 cm) of the objective cube's vertices, the frame of the cube turns green. If the target box is selected and kept green for 0.8 seconds [8], it will disappear and a success sound will be played indicating one docking operation is complete. The user then proceeds to dock the next target box. After docking the three target boxes, one trial has been completed and the system automatically generates three new target boxes for the next trial.

Our hypotheses are:

• H1: For 100% box size, OTS and OH will outperform S+W because S+W always engages scale and for the 100% box size this adds extra mental and physical effort to avoid changing the box size.

• H2: For the 50% and 200%, OTS and S+W will perform faster than OH because they allow simultaneous control of scale, while OH requires switching between 6DOF and Scale mode.

• H3: For the 50% and 200%, S+W will perform faster than OTS because it only requires engaging a single button to engage scale, while OTS requires the user alternatively engage and disengage the secondary scale button.

• H4: Overall, completion times for the 100% box will be faster than for the 50% and 200% percent cases due to the lack of need to scale.

• H5: Overall box sizes, OTS and S+W will outperformed OH, because from H3 they should dominate the scaling conditions and our protocol has 2 scaling conditions and 1 non-scaling condition.

Twelve unpaid students from the Computer Science and Computer Engineering department with little or no experience using 3D computer graphic applications participated in the study. Participants were required to tell the distance differences of different boxes in the scene and distinguish the colors of the box frames and faces.

For each object manipulation technique condition, there are two blocks: a training block followed by a 6 trials of experiment block (18 dockings total). Presentation order of manipulation technique condition was counter-balanced between participants. During the trials, the completion time for each target box are logged. All participants successfully finished the study in 80 minutes.

3.7. Results

3.7.1 Quantitative Results

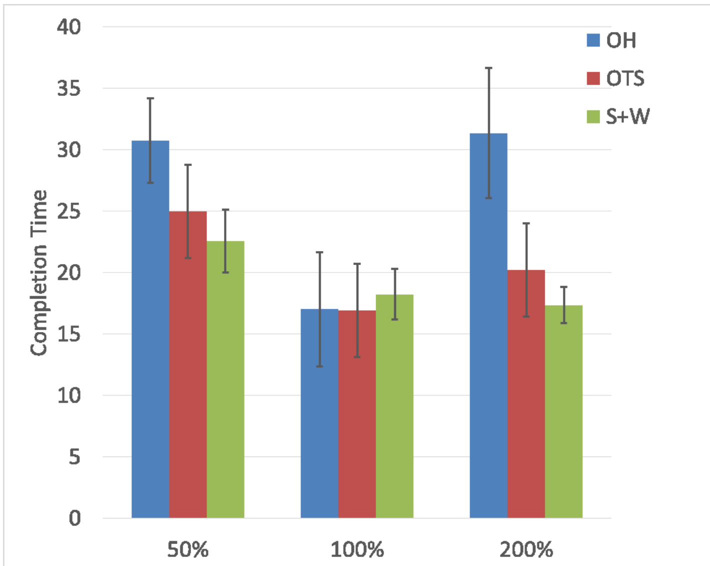

Figure 3.6 Completion time for different box sizes: 50%, 100% and 200% by different manipulation techniques. Bars show 95% confidence intervals.

We used a 3×3 repeated measures ANOVA and included presentation order as the between-subjects factor. Manipulation technique condition (value set {One-handed (OH), Spindle+Wheel (S+W), One-handed with Two-handed Scale (OTS)}), and target box size (value set {50%, 100%, 200%}) are the two variables manipulated within participants. The result shows a significant interaction of manipulation technique and box size on task completion time ($F(4, 44) = 9.486$, $p < .001$, $\eta_p^2 = .463$).

There is a significant simple effect (Figure 3.6) for 50% box size ($F(2, 22) = 10.908$, $p = .001$, $\eta_p^2 = .498$). LSD comparisons show that OH (M=30.76, SD=6.09) has slower completion time than OTS (M=24.99, SD=6.72, p=.003) and S+W (M=22.56, SD=4.52, p=.001). This partially confirms H2. However, there is no difference between S+W and OTS (p=232). This does not support H3.

There is also a simple effect on 200% box size (F (2, 22) = 18.883, p <.001, η_p^2=.632) OH (M=31.33, SD=9.36) has slower completion time than OTS (M=20.2, SD=6.71, p=.003), and S+W (M=17.34, SD=2.62, p <.001). This confirms H2. However, there is no statistical difference between S+W and OTS (p=.127). This does not support H3. Surprisingly, there is no simple effect for 100% box size (p=489) which fails to support H1. This indicates that S+W and OTS outperform OH on task completion time for 7DOF tasks.

For the main effects, there exists significant difference among different box sizes (F (2, 22) = 30.074, p <.001, η_p^2=.732). LSD comparisons show that 100% box size (M=17.1, SD=4.27) has faster completion time than 50% (M=26.1, SD=6.38, p <.001) and 200% box size (M=26.1, SD=8.7, p <.001). This confirms H4.

In addition, 200% box size has faster completion time than 50% box size (p=.046). This was unexpected, however, it corroborates Cho and Wartell [20] study of bi-manual, 7DOF (multi-scale) navigation. They suggest in bi-manual tasks users found it easier to scale down (bring hands together) than to scale up (brings hands apart).

Finally, there is a significant main effect on task completion time for interaction techniques (F (2, 22) = 16.195, p<.001, η_p^2=.596). The LSD comparisons indicate that the completion time of both OTS (M=21.2, SD=7.33, p=.002) and S+W (M=21.85, SD=5.06, p<.001) are faster than OH (M=27.08, SD=8.82). This confirms H5. However, there is no significant difference between OTS and S+W.

3.7.2 Subjective Results

When asked which interaction technique (OH vs. S+W) is better for rotation (APPENDIX A/Post-Questionnaires), six answered S+W and the other half answered OH. Eight answered OH is better than S+W for translation, three answered both are equivalent, and one answered S+W. When asked which interaction technique is better for scaling, four answered OTS, three rated S+W, three rated OH, one answered OH and OTS are equivalent and one answered S+W and OTS are equivalent.

Regarding the question about which technique is most intuitive, five answered OTS, four answered S+W, two answered OH and one answered OH and OTS are equivalent.

Table 1 Qualitative Result for OH, S+W and OTS comparison. Individual participant preferences are labeled S1 through S12.

	Rotation	**Translation**	**Scaling**	**Intuitiveness**
OH	(2) S2 S12	(11) S2 S10 S11 S1 S3 S4 S6 S7 S8 S9 S12	(4) S3 S4 S7 S9	(3) S3 S4 S11
S+W	(6) S3 S6 S7 S8 S9 S11	(4) S2 S10 S11 S5	(4) S2 S10 S11 S12	(4) S2 S7 S8 S9
OTS	(6) S1 S2 S4 S6 S10 S12	(3) S2 S10 S11	(6) S1 S5 S6 S8 S3 S12	(6) S1 S5 S6 S10 S12 S11

Overall, seven of twelve participants preferred the OTS, three rated S+W and one rated both OTS and S+W are equivalent. Participants rated arm fatigue after finishing the experiment for each interaction condition (on a 7-point Likert scale, 1 no fatigue to 7 very painful). There is no significant main effect on arm fatigue rate for interaction condition (χ^2 (2) = .054, p>.05, rates were: OH=1.96, OTS=2.0 and S+W=2.04).

3.8. Discussion

H1 predicted that for 100% box size both OTS and OH will outperform S+W because S+W always engages scale and in the 100% box size this requires additional physical and mental efforts to maintain a constant scale factor. However, the results do not support this (i.e. OTS, OH and S+W perform the same). In contrast, Cho and Wartell found that OH and a modified Spindle+Wheel (that separated scale with a secondary button) both performed faster than Spindle+Wheel for their 100% box size trials. However, their experiment explores 7DOF travel, adapting Spindle+Wheel using the scene-in-hand metaphor, not 7DOF object manipulation as done here.

The difference in outcomes might be explained as follows. Our manipulation task requires a selection step; the manipulation cannot be engaged until the cursor is inside a target box. For Cho and Wartell's 7DOF travel, the travel user interaction is engaged immediately upon button press without requiring the cursor to be inside the target. In the 100% case, their average completion times were 10.6s, 12.1s and 15.5s for OH, SWS, and S+W respectively. For us, in the 100% case, the averages are 16.4s, 16.5s and 17.34s for OTS, OH and S+W. The increase may be explained by the extra time required to move the cursor to the target box for a selection step. Possibly on average this adds an equal increment across all three conditions, leading to a lesser overall percentage difference between interaction techniques and hence causing a lack of significant performance difference between the interaction techniques. A future modified version of our experiment, that uses 7DOF travel instead of 7DOF object manipulation, might find OTS performs better than S+W for the 100% box size.

Another possible explanation is our sample size is small and the low statistical power of the experiment is unable to detect small effects. Alternatively, even one participant could affect both the averaged value and F value greatly.

Moreover, we noticed during the S+W user study, users tend to mistakenly rotate two hands simultaneously to perform the wheel operation which means maybe our current design about the wheel operation is not intuitive. Thus, we may change the wheel operation and compare it with the current version.

According to the users' feedback, most of them prefer OTS than S+W, and they reported several reasons: 1. S+W always requires both hands to be raised even for target selection or translation which obviously not necessary to resort two hands; 2. for small rotation adjustment, one-handed rotation definitely more convenient than S+W which requires both hands with relatively large amplitude motion; 3. as for continues big rotation sequences, however, one-handed method seems to be less smooth or wrist tiresome then two-handed rotation; 4. S+W caused more efforts for the docking task. Users reported hard to control the size and tiresome during the 100% box manipulation; 5. Users tend to mistakenly rotate two hands simultaneously to perform the wheel operation which means maybe our current design about the wheel operation is not intuitive. Thus, considering user's preference which is of high importance to the interface designer, we will give the user the option of Spindle+Wheel or OH method; otherwise use OH.

3.9. Implications for Design and Future Work

According to the quantitative data analysis, users' feedback and observation from the investigator during the user study, we could summarize the implications for future design based on our buttonball based manipulation techniques as follows:

1. Isotonic position control may benefit object manipulation.

Although in OH technique, switching selection button and scaling button on a single button ball could increase docking completion time. However, 8/12 users preferred the isotonic position control for the scaling compared with 4/12 who indicated isotonic rate scaling control. Moreover, Zhai et al. [8] pointed out that isotonic position control yielded much better performance than isotonic rate control. Thus, rate scaling control design in the OH technique may also contributed longer completion time.

2. Separable functionalities of DOFs (Require further proof)

As we explained in section 3.8. Separated control of scaling may benefit object manipulation.

3. Bimanual control of for high DOF task may perform better than manipulation in one-handed mode since both two bimanual techniques (OTS and S+W) outperformed OH technique.

4. Provide OTS only unless specially required. Although we haven't found out significant difference in quantitative analysis in this experiment, however, more participants preferred OTS than S+W. Thus, if satisfying each individual user's preference is of high importance to the interface design, give the user the option of S+W technique or OTS technique. Otherwise, use OTS.

5. Intuitive and efficient direct movement mapping. None of the users in this user study had experienced 6DOF input devices before, all of them gave positive feedback about the intuitive and efficient control about these techniques.

6. Fatigue problem. All participants complained about the arm fatigue after the more than 1 hour manipulation test.

CHAPTER 4: OBJECT MANIPULATION WITHOUT FATIGUE

In this chapter, several manipulation techniques were designed for evaluation based on the purpose of finding out efficient and intuitive method without obvious physical fatigue and absorbing advantages from conventional input devices.

Conventional mouse was chosen as one of our input devices in this section. Because one reason of mouse's preeminence is that most users of 3D graphics applications do not work exclusively in 3D; rather, in most cases a user is likely to frequently switch between 2D and 3D applications [30]. In addition, many 3D applications usually require a substantial amount of 2D interaction - manipulating 3D objects in 2D views as well as the usual 2D tasks of selecting items from menus, typing text, etc. Practically all existing 3D devices, however, perform poorly in 2D tasks when compared to the mouse [30]. Thus, the ability to perform reasonably well for both 2D and 3D tasks is critical for an interaction technique to be applicable in real applications.

A three-dimensional tracker, such as the Polhemus 3SPACE or Ascension Bird, is a three dimensional absolute-position locator. While, a mouse is a two-dimensional relative position locator. The three-dimensional tracker reports its position in three-space relative to a user-defined origin. A mouse, in comparison, requires two operations to manipulate three variables. One commonly used design for mapping three variables (such as x, y, and z for zooming and panning) onto a mouse assigns of the variables (x and y) to be input simultaneously in normal operational mode and the third (z) to be controlled through a mode change button that temporarily turns the mouse into a one-dimensional slider [31]. We think this kind of mapping designs are not the most efficient way for mouse control.

Theoretically, a mouse is a free-moving, i.e. isotonic device. When using such a device, the displacement of the device is typically mapped to a cursor displacement (position control). While, for isometric devices, they do not move by a significantly perceptible magnitude. For elastic devices they are spring loaded. When tension is released from the handle (such as a joystick), the handle returns to a null position. Typically these devices work in rate control mode, i.e. the input variable, either force or displacement, is mapped onto the velocity of the cursor.

When used in rate control, an isometric device offers the following disadvantages [7]:

1. Rate control is an acquired skill. A user typically takes tens of minutes, a significant duration for learning computer interaction tasks, to gain controllability of isometric rate control devices.

2. Lack of control feel. Since an isometric device feels completely rigid, insufficient feedback is provided to the user at the kinesthetic channel. Kinesthetic (or proprioceptive) feedback can be critical to user's control performance.

Thus we decided to choose devices which could enable rotation and position manipulation both to be position control.

A bimanual 6 Degree of Freedom (DOF) manipulation technique based on a hybrid 3D cursor driven by the combination of trackball and mouse technique (TM technique) is presented in this chapter. This technique allows the user to move the cursor to the target location in a 3D scene by following a straight or curved path. A preliminary user study was conducted to compare the technique with a traditional 3D widget technique driven by a keyboard + mouse (KM technique) and a technique based on the combination of SpaceMouse and conventional mouse (3M technique) in 6DOF docking task. In the study, participants could perform the docking task steadily by using standard form of input devices without physical fatigue. The result shows that in this experiment, the proposed TM is more efficient than the traditional KM. Although TM has similar efficiency as the 3M, its adjustment time is significantly less than 3M. Moreover, participants with high mental rotation test (MRT) score revealed significantly more efficiency with TM compared with 3M.

4.1 Introduction

3D modeling and model review are widely used and become indispensable in various fields including engineering community, film industry, game development, architecture, etc. The working system configuration is basically the conventional desktop environment. For years, the mouse + keyboard inputs dominate these 3D interactions and most of the mappings from the physical to virtual movement rely on 3D widgets (manipulators) [32]. However, since the mouse moves on 2D surface and has less DOF than the 3D objects to be controlled, the conventional object manipulation technique has issues with intuitiveness and efficiency.

Previously, researchers tried to improve the efficiency and intuitiveness by using higher DOF devices which could provide more flexible control and efficient movement in designed experiments. For instance, the 6DOF FingerBall enables direct mapping between the physical and virtual object movement which is regarded to be natural [7]. However, lesser physical support with these hand held devices, introduces greater arm fatigue. Recently, due to the progress of computer vision, besides the algorithm, but also the depth cameras, more free hand interaction has been introduced. But unreliable tracking with hand hovering in free space made them seems still not suitable for long duration or precise tasks. Others considered and analyzed the advantages and bad features of the conventional mouse and tested various mouse modifications for enhanced interaction abilities. However, their works seems to be gliding the lily.

In this paper we try a different metaphor of mapping but use the conventional device combination in order to reduce compatibility gap with the current dominant prevailing keyboard and mouse technique and expect wider acceptance with real users. In order to provide a more intuitive and efficient technique which could be suitable for long time usage and precise tasks, we present a bimanual object manipulation technique based on the combination of trackball and mouse. The trackball has 3DOF and direct mapping to the virtual object rotation in the desktop environment. The mouse controls translation through a movement conversion based on a virtual plane. This division and cooperation of translation with rotation control is confirmed by our docking evaluation to be a relative efficient method.

Our contributions are: 1) the design and implementation of a novel bimanual plane riding technique through the experimental exploration of several design factors; 2)

The comparison to current dominant and popular techniques for both precise and coarse control; 3) explored the effect of spatial ability on the manipulation techniques.

4.2 Related Work

4.2.1 Input Hardware

Many previous works focus on developing various input devices for more efficient object manipulation in their specific experiments.

Free-moving 6DOF position-control device may be the easiest type of devices come to mind for 3D manipulation improvement. These devices allow the physical movements to be mapped directly to virtual 3D object movements which provide more intuitive and efficient operation [7] [10]. Some researchers also use Polhemus FastrakTM motion tracking which has precise 6DOF tracking and little latency as the basis for their modified 6DOF input devices [9] [11]. However, they introduced significant fatigue in a short time, which means these devices are not suitable to be applied for prolonged tasks. Recently, there are some experiments which tried to achieve ultimate isomorphic input controller with bare hands based on various vision censors or their combinations [29] [33]. But they could introduce greater arm fatigue and have precision issue. Besides, anatomical limitations of the human limb [11] are also one of the possible causes for application promotion.

With the exception of a keyboard, the mouse is and probably the most frequently used input device. Since intensive mouse work dominates some graphical area such as in computer-aided design (CAD), some researchers tried to augment the standard computer mouse and modify it to be more suitable for 3D interaction while keep the advantages it already has. Balakrishnan et al. [30] designed the RockinMouse, which is a mouse like tilt-sensing input device with a curved base from that an additional DOF is obtained. It was shown to be superior to the mouse for placement tasks. Compared to RockinMouse, the VideoMouse [34] is a device with similar form factor but allowing for two more DOF (z-axis rotation and translation) by using a camera. One limitation of this design principle is that the narrow rounded surface restricts tilting degrees. Another problem we suspect is that these mouse modifications actually broke the most important advantages of the conventional mouse: stability and familiarity. They could also introduced ergonomic or related issue.

Froehlich et al. [35] introduced two 6DOF desktop input devices: GlobeFish and GlobeMouse, which separate translation and rotation at the device level: translation is isometric, or elastic rate control, and rotation is isotonic using a 3D trackball. The performance of these devices was relatively better compared with another commercial device: SpaceMouse [12]. However, for one thing, we think their device may not be well shaped for real users and may not be so easy to hold for long duration usage compared to standard mouse. For another thing, most users of 3D graphics applications do not work exclusively in 3D, rather, typically a user is likely to frequently switch between 2D and 3D applications. Thus, we are not sure if these devices are suitable for both 2D and 3D interactions. Moreover, translation mode is isometric rate control which was considered to be less intuitive and preferred compared to isotonic position control. We will expand this point later. While, for the Roly–Poly Mouse [36], although the translation is under position control, the rotation turns out to be rate control. Moreover, we doubt this form factor which has no flat surface for users hand to rest on is comfortable for long duration usage or easy to use for 2D interaction tasks which is of intensive operation also in CAD related 3D tasks.

Computer vision based such as 3 gear system [33] allow users to use bare hands for 3D interaction. But they could introduce greater arm fatigue and have precision issue about the tracking [37] [29].

Many 3D interaction techniques based on 2D input devices use virtual 3D widgets (manipulators) which convert the cursor movement on the 2D screen plane into the movements in 3D space [32]. Many of these manipulators require a relatively complicated combination of menu selections or keystrokes while still only allowing movement in fixed directions [38]. This kind of interaction metaphor dominates commercial CAD/CAE software such as Maya, AutoCAD, Rhinoceros, Solidworks etc. Related modifications and improvements have not been widely adopted in the market place [39]. Although they do not have fatigue problems because users get desk surface support during the manipulation and could rest part of their arms on the desk, but compared with 6DOF input devices, they are slower [11] and reported to be more rigid. Thus if we use the conventional devices we may want to develop new mappings between the hardware and the virtual object movement for more efficient and intuitive manipulation.

4.2.2 Interaction Techniques

Many 3D interaction techniques based on keyboard + mouse input devices use virtual 3D widgets (manipulators) which convert the cursor movement on the 2D screen plane into the movements in 3D space [38] [40]. Many of these manipulators require a relatively complicated combination of menu selections or keystrokes while still only allowing movement in fixed directions. This kind of interaction metaphor dominates commercial Computer Aided Drafting (CAD) or Computer-Aided Engineering (CAE) software such as Maya and AutoCAD.

Recently a more accessible and natural interfaces was proposed, which try to allow sketches–hasty free hand drawings to be used in the modeling process. Schmidt et al. [39] use gestures not to manipulate an object directly by standard 3D transformation widgets, but initiate a transient operation widget by mouse strokes. The user can then interact with the widget to manipulate the object interactively. For example, a simple linear stroke that crosses an object initiates a translation widget, which is an arrow that can be dragged back and forth to translate the object. An obvious benefit is that the motion directions could be more flexible than standard widgets. However, mapping a 2D sketch to a 3D modeling operation is not easy to implement, may introduce ambiguity [40]. Moreover, since the widget orientation is defined by the cursor stroke direction from the mouse movement, it seems not easy to control for precise work. Also, multiple strokes are required before dragging, rotation, etc. which could increase completion time and complexity. Since there is no formal evaluation of this technique and no comparison with other manipulation methods have not been reported, its key benefits are difficult to assess.

According to the opinion of some experienced CAD students and expert users, the standard CAD interface could display compound 3D widget which provide scaling and translation manipulators the same time around the object. This is convenient for constant switch between scaling and translation operation during 3D modeling process. However, for the sketch–based method, additional strokes are required if the user want to switch from translation operation to scaling or vice-versa. Possibly due to the reasons we mentioned above, we did not find out this technique be adopted by commercial CAD software or practical usage. To our understanding, these widget variations do not actually jump out the traditional motion mapping mode. We propose a different form of mapping and expect it reduce operation complexity and increase manipulation efficiency.

4.3 Bimanual Plane Riding Technique

We present the Trackball + Mouse Technique (TM technique to create a manipulation mode which is based on relatively traditional devices users familiar, while avoiding or improving the rigid conventional manipulation techniques commonly used with these devices. This means an alternative way to map device input signals to 3D movements is required. We expect our method could be applied to desktop computer 3D CAD/CAE software and used for improving 3D manipulation efficiency with fluent control.

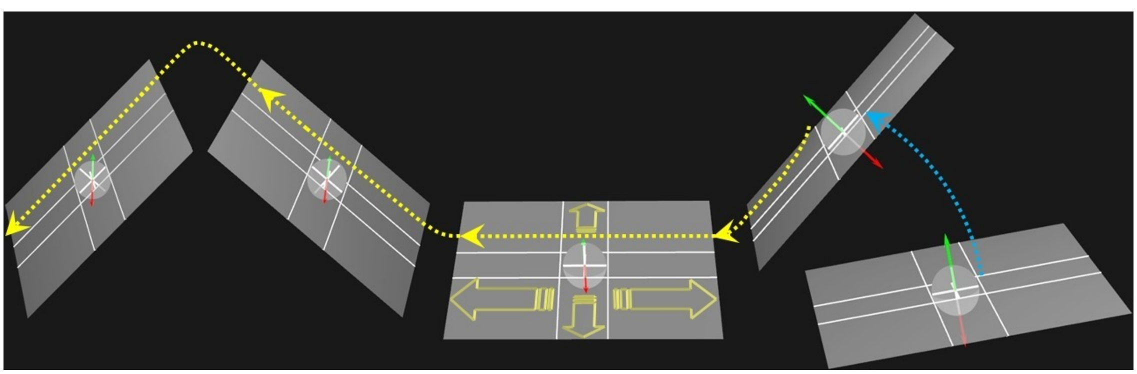

Figure 4.1 The bi-manual 3D interaction technique uses a mouse and trackball to control a 3D cursor. The cursor is a grey square with a transparent sphere at its center and a pair of arrows (red and green) through the sphere. The dotted path above is an example of a user controlled trajectory of the cursor. The trackball controls cursor orientation while the mouse translates the cursor. In the default “plane-parallel” mode, the translation is within the plane embedding the square. The yellow dotted trajectory occurred in this mode. The user can switch to “plane-perpendicular” mode in which cursor translation is within a plane perpendicular to the square. The blue dotted trajectory occurred in this mode.

4.3.1 Background

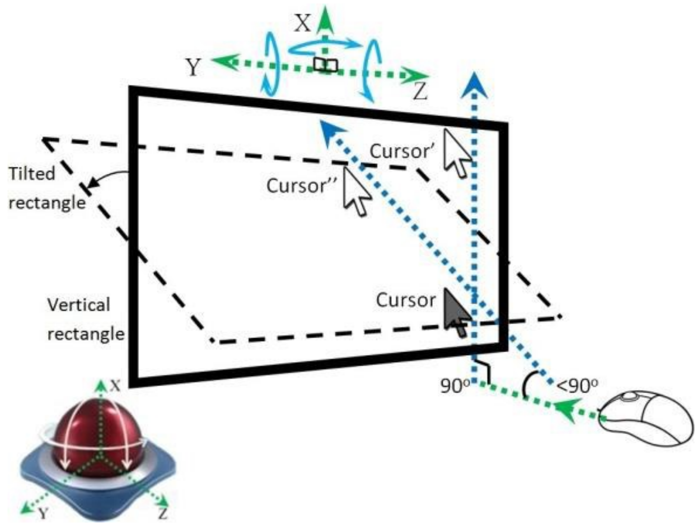

Figure 4.2 TM Technique illustration: 3DOF trackball and cursor movements in planes.

Usually, the mouse cursor is restricted on the screen plane and the mouse movements on the desk are not consistent with the cursor movements. For instance, the forward moving mouse will trigger an up moving cursor with an almost 90 degrees angle between their movement directions (Figure 4.2: bold screen frame with cursor motion from location Cursor to Cursor'). Much research about the mouse interaction is limited to this traditional mouse cursor movement [41]. While a wide range of users are used to this kind of mouse cursor motion mapping, we hypothesize users could also easily understand a mapping where the mouse cursor movement includes angles that are smaller than 90 degrees (Figure 4.2: tilted plane with cursor motion from location Cursor to Cursor"). Thus, we create a 3D virtual plane and allow the cursor motion within this plane instead of the screen plane. Then, the cursor can slide to any location in the 3D environment by changing the tilt angle of the plane. Further, we use a trackball that has full 3 rotational degrees of freedom. Since the orientation of this plane is controlled by the user, the cursor translation is more flexible compared with traditional virtual widgets (manipulators) which essentially only allow movement along the fixed axes or within an individual Cartesian coordinate plane.

Previously, Edwards created a Cutplane constrained to remain within a bounding reference room [42]. However, the Cutplane only moves in directions normal to itself even for the “unconstrained cutting plane” mode. Selection of features (vertices and objects) is accomplished via crosshair that is constrained to remain within the Cutplane. Mouse movements are converted into rotations or translations of selected object by pressing down different mouse buttons. Their method used a single mouse and no user study is performed. While, our 3D cursors shape and size differ because our goal is controlling 3D cursor for general flexible 6DOF manipulation rather than just rigid movements.

The Desktop Bat [43] is a customized mouse that combines isotonic xy translation with elastic yaw-pitch-roll of the dome on the top of the mouse. Their “Relative to Eye Metaphor” for 3D cursor manipulation is appears similar to our device-to-cursor mapping in our TM technique. However, the dome acts as an isometric input and no evaluation of this device in comparison with others has been reported. So the key issue about usability of coordinated 5DOF device operation is unknown. Moreover, the visual representation of their 3D cursor is unclear.

4.3.2 Mechanism

Since previous study revealed the advantage of the conventional mouse especially in placement task, we still resort the mouse to handle the translation of the 3D cursor [4] [44]. The cursor translation driven by conventional mouse is restricted to a virtual cursor plane embedding the cursor square with the motion direction following rules analogous to resolution of forces.

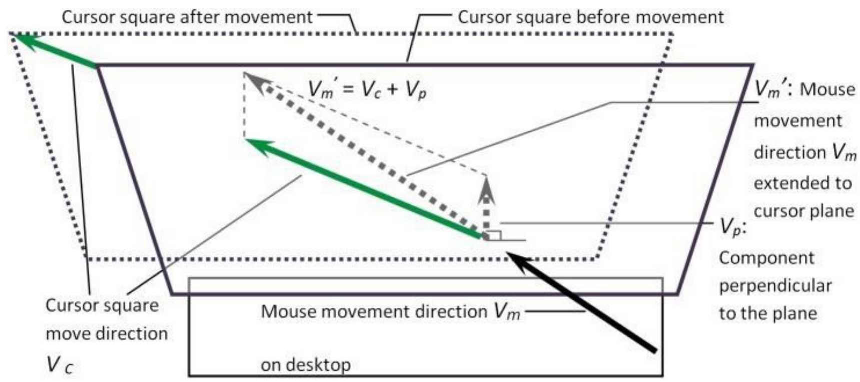

Figure 4.3 Methodology illustration: Movement mapping between mouse and cursor (square) motion directions in a Top-down perspective view

When the mouse is moved in a direction Vm on the desktop (Figure 4.3), the direction of the motion is extended directly onto the cursor plane location (Vm') and resolved into a perpendicular component Vp to the cursor plane and a component Vc on the plane. By default, we assume the cursor can only be translated on the cursor plane, and the movement perpendicular to the plane is obstructed. The moving direction on the plane is defined by the resolved component Vc. For more efficient operation, when encountering the intended moving direction close to the plane normal, we could disable movement in Vc direction and enable the cursor movement perpendicular to the virtual plane with the direction of another resolved component Vp. In either case, the resolved component Vc and Vp only represent the movement directions. In any cursor plane orientation, the movement speed or magnitude is consistent.

4.3.3 Implementation

One of the most important features about our Trackball + Mouse (TM) technique is to use the “conventional” devices to achieve steady, efficient and natural way of interaction by using a cursor square as a medium with maximum backward compatibility with current dominant prevailing keyboard and mouse techniques that could be very promising to be applied to current CAD or related desktop/laptop graphics, which require precision, without fatigue. Moreover, using trackball and mouse ensures ease of device acquisition which is an important aspect of input device usability [7] and also ergonomics issue. Many newly shaped devices such as the GlobeFish and GlobeMouse [35] or other mouse variations [45] [30] [46] [34] are not widely used and may be caused by such usability issue. For instance, GlobeFish and GlobeMouse separate translation and rotation at the device level: translation is isometric, or elastic rate-control, and rotation is isotonic using a 3D trackball. The performance of these devices was relatively better compared with another commercial device: SpaceMouse [12]. However, for one thing, we think their device may not be well shaped for real users and may not be so easy to hold for long duration usage compared with a standard mouse. For another thing, most users of 3D graphics applications do not work exclusively in 3D, rather, typically a user is likely to frequently switch between 2D and 3D applications. Thus, we are not sure if these devices are suitable for both 2D and 3D interactions. Moreover, translation mode is isometric rate control which was considered to be less intuitive and preferred compared to isotonic position control as explained blow.

Moreover, in various research studies, the conventional mouse can outperform higher DOF devices [4] [47]. A recent study [44] of the SpaceNavigator, a popular and high DOF input device, showed that the mouse outperformed the SpaceNavigator in a 3D placement task which required object translation but no rotation. In addition, the potentially greater cost of some higher DOF devices may explain their limited adoption in the market place for common 3D software.

Different from standard 3D widgets or recent enhancements which still follow the mode which set the mouse cursor floating on the screen plane, we created a hybrid 3D cursor which has a cursor square to indicate the plane of translation motion and a spherical core centered in the cursor square indicating the center of rotation and the point of selection (Figure 4.1). To enhance the perception of plane orientation, there are two pairs of bright parallel lines on the square and lighting effects to generate view-dependent cursor square reflection. The hybrid cursor is translucent which allows the user to see objects behind it and can also enhance depth perception [48] since features displayed in front of it are brighter than ones behind it. We added two arrows pointing to opposite directions from the cursor center. When the cursor moves on the cursor plane, the two arrows are located on the intersection of cursor plane and the plane perpendicular to the screen plane. When the cursor moves perpendicular to the cursor plane, the two arrows appear perpendicular to the cursor plane. In either case, the green arrow always points to the cursor's movement direction triggered by the forward mouse movement.

A trackball and a standard mouse are used to control the movement of the 3D cursor. The trackball, supports 3DOFs rotation along all 3 Cartesian axes (Figure 4.2). This allows control of the attitude of the cursor on all 3 Cartesian axes. The cursor square always rotates along the same absolute world axis as the rotation axis of the trackball despite its attitude. For instance, in Figure 4.2, the trackball and cursor square have the same Cartesian axes, if we rotate trackball along X axis (white curved arrow), both dotted and solid squares will rotate along X axis with the same direction (light blue curved arrow). The mouse controls the position of the cursor. By default the cursor movement is restricted to the current cursor plane. The user could move the mouse while rotating the trackball to allow the cursor to move on a curved path similar to the aerobatic maneuvers as indicated dotted yellow line in Figure 4.1. Additionally, when the right mouse button is pressed down, the cursor translates in the perpendicular direction of the cursor plane as indicated by dotted blue path in Figure 4.1.

The magnitude of cursor translation is constantly proportional to the displacement of mouse on desktop (Position Control) independent of the cursor square's attitude.

In this bimanual manipulation, the user uses her less-dominant hand to control the trackball, while the dominant hand to control the mouse. To manipulate an object in the virtual environment, the user places the place 3D cursor's spherical core inside the target. Then, the target box is selected by pressing the left mouse button and its movement is attached to the cursor movement. For the rotation, it is a direct mapping between the trackball and the target. That is, the rotation direction of the target is exactly the same as the rotation direction of the trackball, while, with different speed due to the hardware limitation.

4.4 Benefit of Our Bimanual Control

Since we choose the combination of trackball and mouse as input devices, our interaction turns out to be a bimanual design. Previously, two-handed input seems to be suitable for a wide range of tasks in 3D interaction when designed properly [49]. Some previous experiments demonstrated that two-handed techniques were easily learned by novices and could improve the performance for both novice and expert users. Although using two hands for three-dimensional interaction is not in itself a new idea, for our desktop input design, the bimanual manipulation has many advantages in different aspects according to previous experiments and principles discovered.

4.4.1 Isotonic Position Control

One feature or advantage of our technique (TM) is that both mouse and trackball we choose are isotonic devices and the movement mappings from the devices to the virtual environment are of position control. An isotonic position controller is a more "natural" means of interacting with a virtual environment than an isometric rate controller [16]. Moreover, isotonic position control is superior to isometric rate control for both translation and rotation [36] [7] [35]. Moreover, the Trackball + Mouse technique combines advantages of the mouse which has the advantage in 3D translation [4] (compared with DepthSlider (mouse+slider), SpaceNavigator, free-space device) and trackball which demonstrated more steady [50], efficient and natural 3D rotation [51] (compared with Magellan/SPACE MOUSE).

4.4.2 Separated DOF Input

The by-product of using two input devices is the DOF separation which could also have contribution to more efficient and steady interaction compared with SpaceMouse, a 6DOF device that requires dexterity as separately controlling the DOF is difficult [35] [16]. Maurice and Milguram found that operators, rather than controlling all 6 DOFs equally, allocate their control to the rotational and translational DOFs separately, and switch control between the two groups. With practice, allocation of control within the translational and rotational subsets increases at a faster rate than across all 6 DOFs together. The result of Veit et al. [52] suggests that the simultaneous manipulation of all the DOF does not necessary lead to the best performances. Zhai and Milgram [11] indicated that for a free-moving position-control device and a desktop rate-controlled hand controller, although the movement trajectories of the elastic rate controller were more coordinated, its docking completion time is was longer than the position-control device. Froehlich et al. [35] pointed out that input devices providing separate controls for translation and rotation could be assumed to perform better than an integrated 6-DOF controller and applied this as a guidance to their design.

4.4.3 Compatibility With Traditional WIMP Interaction

In practical graphical applications such as CAD, model assembly or others, users need frequent switch 2D and 3D interaction. The conventional mouse is assumed to be one of the most popular device for WIMP (windows, icons, menus, pointer) interfaces. However, devices such as SpaceMouse are not well suited for 2D pointing [53]. Thus, if used in the CAD applications, since users are already familiar with the work flow of frequent WIMP interactions typically with a mouse, using the mouse for 3D could provide seamless connection with the currently adopted graphical work procedure.

4.5 Comparison Techniques

To evaluate and compare the usability and efficiency of the TM technique, we integrate the traditional 3D virtual manipulation widgets controlled by keyboard and mouse (KM technique) in our 3D environment. Also, we integrate a current high DOF CAD product SpaceMouse in our system (3M technique). We compared our TM technique with the conventional KM technique and the 3M technique in a 6 DOF (translation + rotation) docking task and discuss preliminary evaluations.

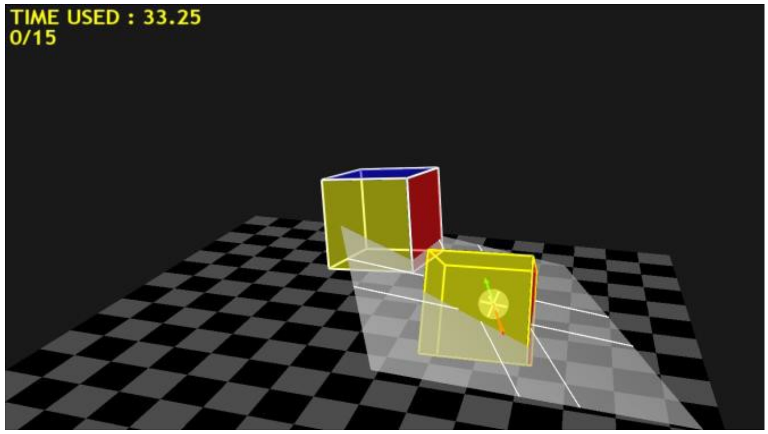

Figure 4.4 TM technique and docking environment

4.5.1 Keyboard + Mouse Manipulation

In order to evaluate the TM technique, we implemented 3 typical 3D transformation virtual widgets (manipulators) (Figure 4.5) which are typically used in modeling software [39]. The DOFs of the KM technique is different from that of the TM technique, but both KM and TM techniques require bimanual manipulation and the KM technique is the dominant manipulation technique used in 3D modeling software. Therefore, we chose to compare of these two techniques with the suggestion that TM has the potential to substitute KM while still using common input devices.

In this virtual widget KM technique, the user's dominant hand controls the mouse for the 7DOF box manipulation. The non-dominant hand presses two keys: 'x' and 'c' and switches between different widgets for Translation and Rotation. When a widget is selected, it will appear around the target box selected earlier by the conventional mouse cursor. The translation widget has 3 arrows which can be clicked and dragged with the attached box along any axis. The rotation widget enables the user to rotate the object along any axis or along any direction by dragging on the circle or on the object.

A B

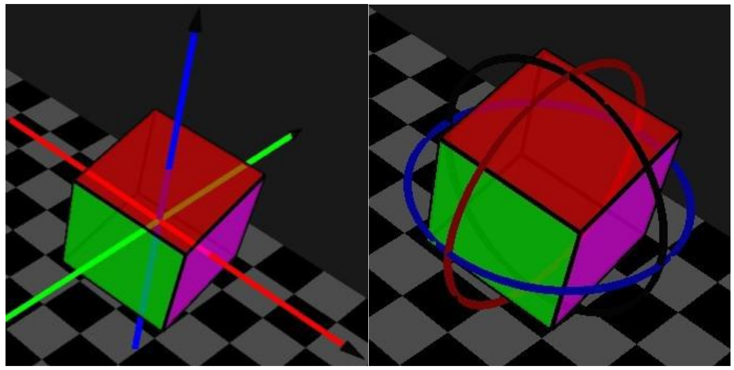

Figure 4.5 Translation Widget (A) and Rotation Widget (B) in KM technique

4.5.2 SpaceMouse Manipulation

To compare TM technique with the currently most popular high DOF input device used in CAD field, we chose SpaceMouse from 3Dconnexion. This device has 6DOF (Figure 4.6 A) and uses a rate control from the cap on top of the device to control rotation and translation at the same time. Since this device is designed to be combined with conventional mouse together, to apply this device in the environment, we use the SpaceMouse to control a 3D spherical cursor. When the cursor is moved inside the target box, the user uses her/his dominant hand to push the mouse button for selection. Then, the movement of the target box is attached to the cap movement of the SpaceMouse.

A B

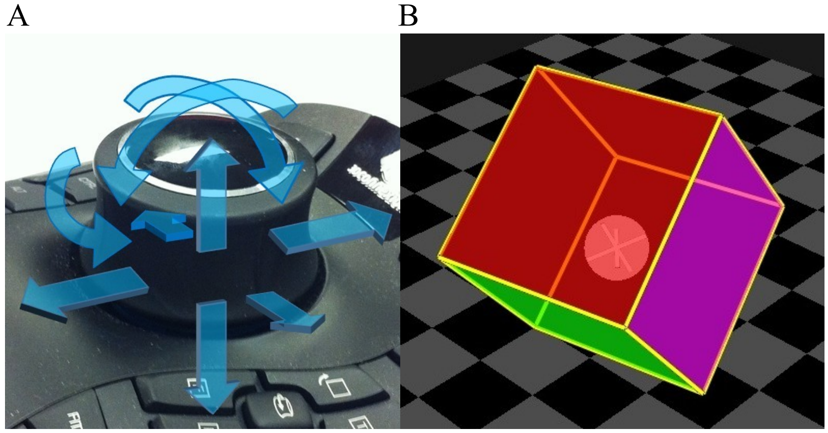

Figure 4.6 Illustration of 3M technique

4.6 Preliminary User Study

The experiment uses a laptop (Thinkpad W530) setup as a simulation of conventional standard 3D modeling environment. We chose Dell USB Optical Mouse w/Scroll Wheel MS111- 9RRC7 - 356WK as the conventional mouse used in each technique.

For TM technique, we chose Kensington Slimblade Trackball (Figure 4.7 A) as the 3D trackball for non-dominant hand. Since the rotation along axes Y and Z (Figure 4.2) has high precision as other common trackball but the X rotation is actually a wheel operation which has low precision, we reduced the rotation signal transmitted to the target to ensure consistent rotation speed at any direction while meeting precision requirement for the current docking task. For our current control-display (CD) ratio [11], when the trackball rotates 360 degrees in any direction, the corresponding target rotation is 90 degrees which means rotation gain to be 0.25.

A B

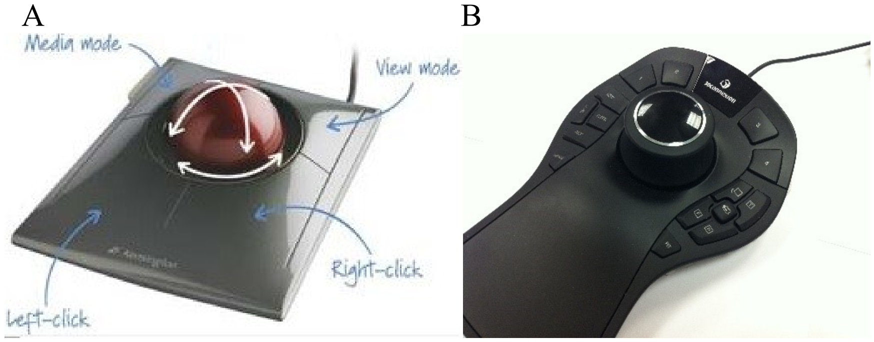

Figure 4.7 Trackball in TM technique (A), SpaceMouse Pro in 3M technique (B)

For 3M technique, we chose SpaceMouse Pro (Figure 4.7 B), because it is one of the more successful 6DOF devices on market. We think we should judge a device in many aspects beside efficiency. Of course, there are many devices that could beat SpaceMouse, but they are not as successful as SpaceMouse. Even for the SpaceMouse, although it has some positive feedback through previous user studies [44] compared with Keyboard + Mouse (3D widget interactions) in some aspects, it is used less by CAD users. One reason perhaps for the absence of wide acceptance is the use of rate control which has been shown to be harder to use, for novice users [35].

Perelman et, al. set and tested the default behavior (default gain factor) of the SpaceMouse and a smaller gain favouring precision over speed and found no significant difference between two gain conditions [36]. We set the gain to the default and slightly reduced it for the user study according to users' opinion. Moreover, the trackball that we used may not have the best gain value for rotation because of hardware limitations. Besides that, there are other factors that could be improved for better TM manipulation such as trackball size, different transfer functions, better visual feedback of the 3D cursor, etc. Thus, we think as an initial basic comparison for different manipulation mechanism, our experiment maybe sufficient.

As for the experiment environment, at first, we considered using orthogonal views. Ortega, M [54] presents IUCA (Interaction Using Camera Animations), an interaction technique for 3D objects manipulation. IUCA allows efficient interaction in a full-resolution perspective view by integrating transient animated transitions to orthographic views into the manipulation task. This work proved that their dynamic orthogonal views was efficient for 3D translation. While, we rejected this option at the very beginning. We presume the dynamic constant view change from perspective to orthographic or vice-versa which is indispensable for this method could introduce eye strain especially for long duration usage. The default environment for most of CAD software which also use widgets for manipulation choose relatively stationary perspective views. We think we should imitate their environment for our experimental study. Second, our focus is the 3D object manipulation techniques instead of camera variation.

Our software is based on OpenSceneGraph and Microsoft Raw Input. A translucent docking box of fixed size is shown at the center of the screen with a random orientation for each trial. One target box with black frames with different sizes are located at random positions above a checkerboard ground plane (Figure 4.4). Each box face has a unique color. The user selects the target box and aligns it with the docking box matching like colored faces via translation, rotation and scaling. Each target box vertex must be within 0.84 cm [11] of the corresponding docking box vertex. In that case, the frame of the cube turns red. If the target box is selected and kept red for 0.8s [8], it will disappear and a successful completion sound is played indicating one docking operation is complete. The user then proceeds to dock the next target box. After docking the target box, one trial is complete and the system generates a new target box for the next trial.

In all three manipulation techniques, the user could use the middle mouse button to change the view angle of the scene similar to many current solid modeling software such as blender, Rhino, etc. When the middle mouse button is pushed down, the left/right mouse movement changes the view azimuth and the forward/backward movement changes the view elevation. Thus, user could get a better sensing of the box pose [55]. Also the keys ‘v’ and ‘space’ could immediately set the environment to top-down view or front view. For the TM technique, the orientation of the 3D cursor doesn’t change with the view which make the cursor to be a tool attached with user’s side which means it doesn’t change the attitude to the user under the camera operation. For the 3M technique (Figure 4.6 B), no matter how the view changes, the cursor movements keep the same intuitive direction to the user. As for the KM technique, the widgets are attached to the target box as the default mode of most CAD software.

4.7 Mental Rotation Test

Because in our previous pilot user study, we found users' feedbacks varies on TM technique. Since TM technique requires the user to understand the orientation of the cursor square in the scene, we think it has connection with users' spatial imagination ability. Thus, before the formal user study of manipulation technique comparison, we gave each user a mental rotation test (MRT). This test was carried out separately from the program test. For this test, we chose Vandenberg and Kuse Mental Rotation Test (MRT) [56]. The test has a score range from 0 to 24, the higher the better mental ability it indicates. Hegarty et al. [57] showed that the MRT has a strong correlation with the performance in mental rotation tasks. Each problem presented a 3D object and four similar images. The participant had to identify the two images in the set that represented rotations of the original object. Our version of the test was administered in the standard way [58], and each participant roughly take 15 minutes to complete this MRT test.

To analyze the data we classified participants into two categories: participants with higher spatial abilities (HA) and participants with lower spatial abilities (LA) [59]. We took the median of the MRT test scores (11) as the metric to decide the partition between the two categories; participants above or equal to the median were classified as HA and those below the median were classified as LA.

4.8 Program Test

We ran a user study on 16 students, from Architecture, Mechanics, Education, Geography and Computer Science. The separate MRT test divide them in to 8 in HA and 8 in LA.

For the manipulation tests, the total time for a single user is roughly 2.5 hrs. Before the formal docking test, each participant has roughly 15 minutes of training with each manipulation technique. They are given instructions and their operation problems are revised during the training block. Then for each manipulation technique, an experiment block requires the participant to finish 15 docking task trials.

4.9 Analysis

We measure the docking completion time of the target box recorded by the program during the users' test. Since we do not consider object selection for current study, the completion time is measured from the point when the target is selected to the point it disappears in the scene. Also, for each docking trial, we divide the completion time into two parts: coarse docking time and precise adjustment time. The watershed is decide by the following rule: each corner of the target box is at -0.84 cm to +0.84cm to the corresponding corner of the docking box and their angle difference is smaller than 13.43 degrees as illustrated in Figure 4.8. Suppose the centers of two boxes coincide, when the angle difference is 13.43 degrees, corresponding corners have 0.84 cm distances.

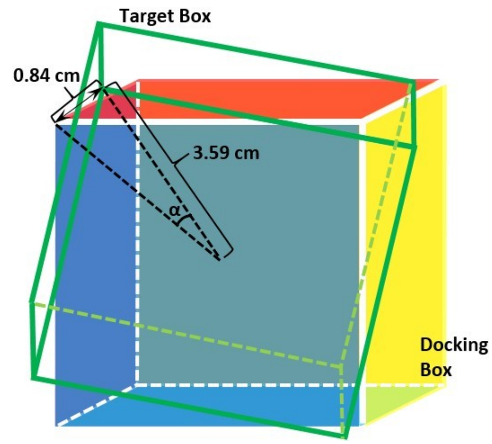

Figure 4.8 Illustration of coarse precise docking watershed

Our major hypotheses are:

- H1: For participants have relatively with high MRT (people suitable for CAD or other 3D related work should have no confusion about cursor square orientation specification), TM will outperform 3M because TM has good features of separate DOFs and isotonic position controls.
- H2: For coarse docking time, 3M will perform faster than TM because 3M is more intuitive for all users and the coarse docking matching requirement should be easy to handle even for isometric rate controls.
- H3: For precise docking time, TM will outperform 3M because isotonic position control should be steadier for small adjustment than isometric rate control.
- H4: For the physical fatigue, including fatigue from arm and hand, 3M will be rated higher than the other two since the isometric rate control is not as intuitive and steady than isotonic position control.

4.10 Quantitative

The result of one-way repeated measures ANOVA shows a significant main effect on task completion time of interaction technique ($F(2, 30) = 54.42$, $p<.001$, $\eta_p^2=.78$).

LSD pairwise comparisons revealed that the completion time of KM (M=100.00, SD=32.27) is significantly slower than both 3M (M= 46.65, SD=15.55, $p<.001$) and TM (M=40.61, SD=15.26, $p<.001$). However, there was no significant difference between TM and 3M ($p = .16$).

On coarse docking time across three interaction techniques, the result revealed a significant main effect, $F(2, 30) = 32.17$, $p<.001$, $\eta_p^2=.68$. Pairwise comparison tests indicated that the coarse completion time of KM (M=59.55, SD=21.92) is significantly longer than 3M (M= 27.44, SD=11.59, $p<.001$) and TM (M=26.99, SD=10.39, $p<.001$). There was no statistical significant difference between 3M and TM ($p=.89$). The prediction (H2) is not supported.

The result also showed a significant main effect on precise docking time for interaction technique condition ($F(2, 30) = 24.43$, $p<.001$, $\eta_p^2=.62$). LSD comparisons revealed that the precise docking time of KM (M=33.70, SD=17.11) was significantly longer than TM (M = 9.98, SD = 4.67, p<001) and 3M (M=16.01, SD=8.91, $p=.001$). Interestingly, the precise docking time of 3M is slower than TM ($p=.01$) which confirms H3.

We separated 16 participants into two groups based on their mental rotation score (high vs. low). For a 3 x 2 mixed multi-factor design, with three manipulation techniques and two levels of MRT score as the independent variables, and box docking completion time as the dependent variable. The analysis shows no significant interaction effect between manipulation technique and MRT level, $F(2, 28) = .09$, $p = .91$, partial $\eta_p^2=.006$. However, for high MRT score group, the result showed there was a main effect on the task completion time of interaction technique ($F(2, 14) = 35.67$, $p<.001$,

η_p^2=.836). Similarly to the result of all 16 participants, KM (M=97.85, SD=35.97) is significantly slower than 3M (M=44.67, SD=17.26, p=.001) and TM (M=35.97, SD=13.49, p<.001). However, 3M is significantly slower than TM (p=.028). This confirms H1.

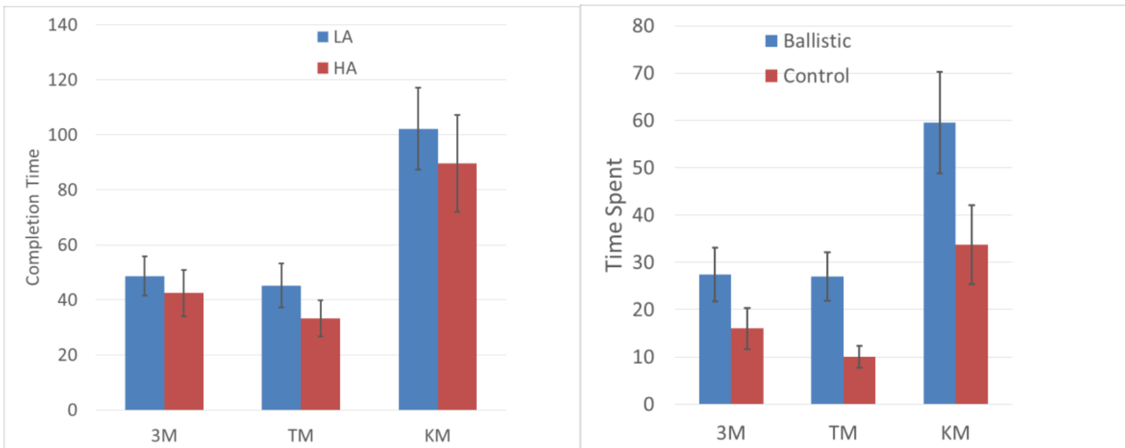

Figure 4.9 Completion time of participants in low mental rotation ability (LA) and in high mental rotation ability (HA) (left), ballistic time and control time in different manipulation techniques. Bars show 95% confidence intervals.

The relationships among two scores from the TM technique completion time and MRT scores were assessed using Pearson Correlation coefficients. There was no significant positive relationship between TM completion Time (M = 40.61.00, SD = 15.26) and MRT score (M = 11.94, SD = 4.82), r (4) = -.31, p =.24. Probably affected by the low power (power of .21 to detect a moderate relationship (R^2 = .3)).

Participants are asked to rate their mental fatigue and physical fatigue after each manipulation condition (on a 7-point Likert scale 1: Not at all through 7: Extremely fatigue). There was no significant main effect on the mental fatigue rate for interaction technique condition ($\chi^2(2)$ = 1.418, p=492). On the physical fatigue rate, however, there was a main effect for interaction technique condition. (χ^2 (2) = 7.385, p=.025). Wilcoxon signed-rank tests with a Bonferroni correction applied ($p<.017$) show that the physical fatigue rate of TM (Median=2.0) is significantly lower than 3M (Median=3.5. Z= -2.787, p=.005). This confirms H4. However, there were no significant differences between TM and KM (Median=4.0, p=.022) and between 3M and KM (p=.964).

4.11 Qualitative

When we asked to participants which interaction technique was the best for the rotation (APPENDIX B/Post-Questionnaires), 10 out of 16 choose TM because they think it is easier to control for precise adjustment by using TM. 6 answered 3M because they think the use of its controller cap like rotating the actual object. Regarding a question about which interaction technique was the best for the translation, 9 out of 16 answered TM, 3 answered 3M, 2 rated KM, 1 answered both 3M and TM and 1 answered no preference. Overall, 12 participants out of 16 answered that they preferred TM and 4 preferred 3M.

Table 2 Qualitative result for TM, 3M and KM comparison. Individual participant preferences are labeled S1 through S16.

	Rotation	**Translation**	**Intuitiveness**	**Preferred Most**
TM	(11) S2 S3 S5 S6 S7 S9 S11 S13 S14 S15 S16	(10) S1 S2 S3 S6 S7 S9 S10 S11 S13 S15	(5) S1 S2 S3 S5 S6	(11) S2 S3 S5 S6 S7 S9 S11 S13 S14 S15 S16
3M	(5) S1 S4 S8 S10 S12	(3) S4 S11 S12	(11) S4 S7 S8 S9 S10 S11 S12 S13 S14 S15 S16	(5) S1 S4 S8 S10 S12
KM		(3) S8 S14 S16		

4.12 User Comments

Architecture students with extensive CAD experience had some of the following comments:

1. “I feel that this (TM technique) is moving towards a much more intuitive use of 3d modeling software. The two hands means instant and simultaneous control of object movement, but at the sacrifice of access to the keyboard. Overall, I’m excited for using this method more.”
2. “3M [is] intuitive and easy to correct errors”
3. “I have not used a trackball before but it was the most intuitive.”

Several comments from engineering students are:

4. (Pro-E User) “For technicians TM is good for work, define manipulate quickly and other further development. For game exploration, 3M is fun.”
5. (AutoCAD user) “TM is the best, it separates rotation and translation which makes it more efficient.”

4.13 Discussion

For 8 participants with high MRT scores, TM technique is significantly faster than 3M technique. Possibly this is because their higher spatial ability allows them to better master TM and it’s separation of rotation and translation compared to the SpaceMouse where intended translations may cause unintended rotation and vice versa. This corresponds with previous research that although some device coordinated better, they are less efficient. Although users could simultaneously operate translation and rotation in 3M technique, but that such parallel action is inefficient. Trajectory analysis actually only reveals stronger coordination across DOFs has less efficient manipulation in completion time [31]. For participants with low MRT scores, actually in each docking test, they took relatively long time to figure out how to rotate the cursor square in order to move the target box to the intended location which for people with good spatial ability should be instant decision.

As expected, TM technique performed better in precise docking phase. Besides, as reported from people in CAD or CAE, they thought TM was more suitable as for applying it to their work because of easier to control compared to SpaceMouse.

According to our observation during the user study, besides the fact that isotonic devices used in TM have no force of resistance, the trackball allows more manipulations from fingers during the rotation control which could make the operation to be more comfortable and introduce less fatigue [60].

We also considered the physical integration of trackball and the mouse. For one thing, we think it might be too complicated for one hand to hold and control all 6DOF and may introduce ergonomic issues. For another thing, Isokoski et al. [61] evaluated devices trackball-mouse, which include both a trackball and a mouse in a single device, in their experiments. They found that no matter in users' preference or the quantitative data analysis, another two-handed configuration outperformed the trackball-mouse input. We think considering the relatively simple mechanical structure of the trackball, it should be not hard to integrate it to the keyboard location. Then, CAD or other users do not need frequent move their hand from trackball to keyboard.

4.14 Conclusion

This experiment presents a bimanual 3D manipulation technique that could be used for 3D modeling and other applications. We perform a user study where the TM is more efficient than the traditional KM. Although TM has similar total completion time to 3M, its precise manipulation time is significantly faster than 3M. Moreover, participants with high mental rotation test (MRT) score had faster completion time with TM compared with 3M. Our intention for TM is to create a technique for users experienced with 3D modeling, potentially further study with high MRT users could reveal more merits of the technique. Moreover, if an idea trackball applies which allows a C-D ratio to be 1, users' experience of TM rotation could be even better [11].

4.15 Implications for Design and Future Work

We summarize the implications for future manipulation technique design based on desktop input devices as follows:

1. Separable functionalities of DOFs with isotonic position control is optimal than integrated DOF functionalities with isometric rate control. (The experiments of previous researchers (4.4.1, 4.4.2); my quantitative analysis (4.10) which TM technique outperformed 3M technique under some circumstances and requirements; and users' preferences for separated isotonic translation rotation controls (4.11).)

2. For high DOF control (6DOF or even higher), bimanual control may be a better choice compared with DOF control using only one hand. Although all three manipulation techniques in this experiment used two hands, however, only TM technique used both hands for 6DOF control on the target box.

3. Desktop support for long duration usage. Compared with experiment in Chapter 3, no participant complained about arm fatigue in this experiment, although this user study took even longer time.

CHAPTER 5: THE ROLE OF INTEGRAL AND SEPARABLE CONTROL

5.1 Background

Previously (Chapter 3), the experiment didn't reveal significant difference between OTS and TH techniques. However, considering Cho's work which found significant difference between integral and separate scaling [20], and also relative small sample size in my user study, further study on the deeper investigation and understanding for the role of DOF separation and integration during the manipulation process is necessary.

According to the theory of perceptual structure of visual information by Garner [62], a multi-dimensional object can be characterized by its attributes in two categories: integral structure and separable structure. Visual information has an integral structure if its attributes can be perceptually combined to form a unitary whole. If visual object attributes show perceptually distinct and identifiable dimensions, they are separable. Jacob et al. [31] conducted an experiment in which subjects performed two 2D object matching tasks that had different perceptual structures (integral location + size and separate location + color), using two input devices with correspondingly different control structures: a three-dimensional tracker and a conventional mouse. Their results support their hypothesis: human performance increases when the perceptual structure of the task matches the control structure of the device. They test two tasks, translation + color matching and translation + size matching, over a range of thresholds. The threshold is the degree of position matching required for completing a match. For their translation + color task, the mouse always outperformed the Fastrak for thresholds of 0 to 0.24 inches (6 millimeters), which demonstrated the superiority of the mouse for precise operation. Their result also indicated that no matter how large or small the matching criterion (threshold), for translation + size task, Fastrak always outperform mouse. This result seems to contradict our impression that simultaneous, multidimensional input (represented here by the Fastrak condition) allows users to work quickly, but at the cost of precision; our impression would suggest the mouse would have outperformed the Fastrak when the required threshold is small.

Bérard et al. [4] demonstrated the advantage of the mouse in precise control in 3D placement tasks. In their experiments, the mouse based technique applied in the 3D placement task follows the rules found by Jacob, because the 3D placement was decomposed into 2D movement sequences in different views which means the control structure of the mouse then matches the perceptual structure of the movements. It seems these results supported Jacob's conclusion. However we cannot simply infer that the result could be similar if the task also required rotation control. For instance, Hinckley et al. [10] showed that a free-space (3D isotonic) device was more efficient than mouse-based interaction for a 3DOF rotation of an object even for high level of accuracy requirement. Furthermore, human performance characteristics when using different devices and movement mappings in tasks that require translation, rotation and even scaling are not clear.

Other researchers claimed that although in theory Jacob's findings were true, but applications also need to consider the users' preference and capability of carrying out integral control [63] [64]. Masliah et al. [16] revealed that most of the time, users manipulate rotational and translational DOF as separate subsets in a 6-DOF docking task. Thus, it seems devices providing separate controls for translation and rotation might benefit object manipulation compared with an integrated 6-DOF controller. Based on this result, Froehlich et al. then claimed that input devices providing separate controls for translation and rotation can be assumed to perform better than an integrated 6-DOF controller [35].

For spatial translation, Veit et al. [63] investigated the separation and integration of 3DOF translation control and divided the task into two phase: ballistic phase (coarse matching) and control phase (precise matching). They found during the ballistic phase (coarse matching), users manipulate all the dimensions of the task at the same time and during the control phase, users try to manipulate specific dimensions individually. They claimed integral control of 3DOF in positioning was suitable for ballistic phase but not the control phase and the separate 3DOF control outperformed integral control for the control phase during the 3D positioning. They designed a dynamic translation technique which took advantages of integral and separate control in 3DOF translation and evaluated their technique to be more efficient in three tolerance conditions. The fact that in the control phase, 3D positioning benefited from separate translation control seems to contradict Jacob's general rule which suggests 3DOF positioning should benefit from integral 3DOF control.

For rotation, Veit et al. [52] evaluated the decomposed and integral control of 3DOF rotation. They conducted an experiment in which users had to orient 3D objects with two interaction techniques, one integrated and the other separated. Their results suggested that the simultaneous manipulation of all the DOF did not necessarily lead to the best performance. This result also seems to differ from the results of Jacob.

According to our previous observation for the 7DOF manipulation during the user study in Chapter 3, in the final control phase, many users tended or preferred to enable 7DOF manipulation control simultaneously (for OTS technique this means enabling scale with pose control) instead of separating them. Moreover, two techniques which could have integral control of 7DOF manipulation outperformed the OH technique which separated the scaling control from rotation and translation. Also, for TM technique, in many cases, users adjusted box orientation and location at the same time in the final tuning.

One possible explanation is that for 6DOF control (translation and rotation only), DOF decomposition could be beneficial for DOFs in a same group that are similar in nature (3DOFs in translation and 3DOFs in rotation). While, as for controls among rotation, translation and even scaling, may have different properties. Even though during the whole docking process, users always separate translation and rotation [35] [16], but it does not prove users do not need integral control of translation and rotation at all during the whole operation. Besides, for the 3D rotation decomposition [52], actually, their work only can prove that a technique (BPCR - Bi-manual Plane Constrained Rotations) providing separate and integral 3DOF rotation works better in large orientation condition and simple orientations than a device which only provides integral 3DOF rotation. (In a "simple" orientation task, the target needs to be rotated around only one axis of the coordinate system).

In their study, the head and hands are tracked using the ART optical tracking system. The users wear two XIST Data Gloves. In their first technique, called IR (Indirect Rotations), the user grabs a 3D cube (called a virtual manipulator) positioned immediately at arms' reach. 3DOF rotation manipulation of the cube rotates a larger 3D shape outside of arms reach. Using the IR technique, users are able to combine the three axes of rotation into a single gesture thus integrating the task's DOF.

The second technique is called Bi-manual Plane Constrained Rotations (BPCR). The user controls a rotation around an axis of the object's coordinate system by moving her finger along the corresponding touch screen axis. The user can use both hands simultaneously or successively to perform rotations by touching the screen. The dominant hand gives her access to two specific axes of rotation and the non-dominant hand gives her access to the third axis. It eases the decomposition of the task by manipulating one axis of rotation at a time. Also, users could manipulate several DOF at the same time by using both hands simultaneously. The users were required to rotate an object to match a given target's orientation.

The results suggest that the simultaneous manipulation of all DOF does not necessary lead to the best performance. It seems their conclusions are the opposite of Jacob et al's. However, actually, their work only demonstrates that a technique (BPCR) providing separate and integral 3DOF rotation works better in large orientation condition and simple orientations compared to a device which provide integral 3DOF rotation. They found most of the time, in the IR technique the user manipulates 2DOF simultaneously instead of 3DOF simultaneously and most of the time, BPCR manipulates 1DOF. However, in each case, there is a small percentage of manipulating 3DOF simultaneously. Although this portion is small, I hypothesize it may be crucial during the control phase.

To have a better clear understanding about the role of DOF separation and integration in 3D manipulation, we designed a series of manipulation techniques with different restrictions to highlight the effects of DOF separation versus integration.

For the input device, we chose a free space buttonball based on 6DOF Polhemus tracker which could provide intuitive direct spatial mapping from physical to virtual environment and has little movement restriction on the users' hands. For the manipulation techniques, all were based on position control which has been proved outperformed rate control for 6DOF docking [11].

I also hypothesize manipulation performs differently in different phases (ballistic and control phases) and between tasks requiring different degrees of precision. Thus, in the experimental design, I examine performance of different tolerances and distinguish the two phases.

5.1.1 Method Selection for Separate & Integral Control Analysis

There are several methods which have been used for analyzing the level of DOF integration and separation in object manipulation.

5.1.1.1 Movement Efficiency

Zhai et al. proposed a measure of quantifying coordination in multiple degrees of freedom based on movement efficiency [11]. For a task that involves N degrees of freedom, the trajectory that has the shortest length in that N dimensional space is considered the most coordinated movement.

They investigate two 6DOF input devices, the Fingerball (isotonic (free moving) 6DOF input device) and the EGG (a 6 DOF device that is elastically constrained and works in rate control) which was considered to be better than the isometric rate controlled Spaceball. For the completion time, for both experiments, the mean trial completion time of the isotonic position control (Fingerball) group was significantly shorter than that of the elastic rate control (EGG) group. For translation, their results illustrates the isotonic position control device was significantly less efficient than the elastic rate control device. For rotation, the rotational inefficiency with the isotonic control device was significantly higher than with the elastic rate control device. Between translation and rotation, the rate control group was significantly more efficient than the position control group.

5.1.1.2 The m_Metric

Instead of measuring the task completion time or the trajectory, the M-metric [16] measures the degree of simultaneous error reduction occurring in multiple DOFs. The M-metric score is the product of simultaneity of control (SOC) and efficiency of control (EFF):

M-metric = SOC × EFF

For the SOC, the normalized error reduction function for each DOF is computed separately. Then the value of SOC is calculated by computing the overlaps between the normalized error reduction curves (Figure 5.1). The EFF component of the M-metric is a weighted average of the ratios of the length of the optimal trajectory for each DOF divided by total actual error reduced for that DOF.

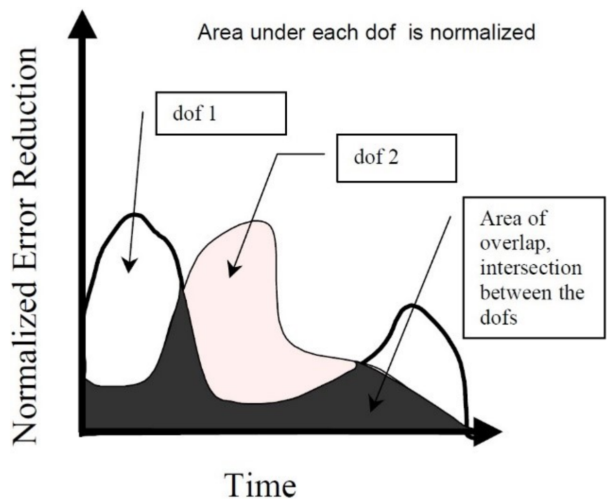

Figure 5.1 A normalized error reduction graph illustrates SOC computation (Figure 1 in [16]. Used without permission.)

6 degree-of-freedom (DOF) virtual docking task experiment conducted by Maurice R. Masliah was based on two devices: An isotonic input device (Fingerball [60] powered by a Flock of BirdsTM (Ascension Technology Corp., Burlington, VT)) and an isometric input device (Spaceball® (Model #2003) manufactured by Labtec Inc. (Vancouver, WA)).

They found that for comparisons between two DOFs, the highest M-metric scores always belonged to the within the three rotation DOFs during isometric rate control. The lowest M-metric scores, for the two-way comparisons, always belonged to isometric rate across translation and rotation pairings. For three DOF pairings, isometric within rotations score was the highest, isometric across rotation and translation score was lowest. This implies the isotonic condition has more integrated operation of translation and rotation than isometric condition and isometric condition has more integrated operation within the three rotation DOFs. However, regardless of which input device was used, subjects tended to allocate control within rotation and translation groups separately.

5.1.1.3 Magenitude of DOF's Separation Measurement

Veit et al. proposed the Magnitude of DOF's Separation measurement (MDS) [52], which also did not depend on the optimal path, to study how users manipulate the three DOF of the orientation task. The calculation is based on the angular velocities around each axis of the 3-D coordinate system. When the MDS measurement is close to 0, the user rotates the object around the three axes at the same time and with the same amplitude. When the value is close to 0.5 the user rotates the object mainly around two axes. Finally, when the value is close to 1, the user rotates the object only around one axis.

5.1.1.4 Method Comparison and Selection

Zhai pointed out that the drawback of the simultaneity measure was that it did not account for the magnitude of the control actions in each degree of freedom. They suspected that as long as all of the degrees of freedom were activated, regardless the amount of input generated, the trial was considered coordinated by this measure. However, the m-Metric method solved this problem by only integrating the overlap area of error reduction rates in different DOFs. Thus, even if users triggered unintended DOFs, their contribution to the final integration should be very small.

The calculation of MDS actually is similar to the SOC computation in M-metric. With 3D rotation for instance, they are both based on the angular velocities around each axis of the 3-D coordinate system. MDS sums up differences while SOC sums up overlaps.

We chose the more comprehensive m-Metric measurement for our quantitative analysis for several reasons. First, the trajectory analysis result of Zhai showed that a more efficient path did not have a faster completion time which is one of the features I am most interested in. Second, I seek a better understanding of the cooperation of rotation and translation which is not easily examined by movement efficiency only. Third, for the control phase, the small repetitive adjustments could be highlighted by accumulation which is included in the m-Metric calculation. Moreover, m-Metric is more generally adaptable than MDS which only focuses on rotation.

5.1 Experiment 1 and 2

To find out and clarify the effect of separation and integration in different phases, I designed two experiments with evaluations of 3D docking tasks.

For the first experiment, I evaluated the effect of integration and separation of 3DOF translation and 3DOF rotation. This experiment only considers the One-Handed based manipulation in 6DOF docking test. According to the observation from my previous user study, I hypothesize that for the ballistic phase, separate control of translation and rotation would outperform the integrated 6DOF control; for control phase, integral 6DOF control would outperform separated translation and rotation. If the experiment results support the hypothesis, I would develop a new technique that separates translation and rotation in the ballistic phase while integrating them in the control phase.

For the second experiment, we add scaling control. Similarly, we apply the 7DOF docking tests to find out if different control could benefit different manipulation phases.

5.2 Experiment 1: Manipulation Technique Implementation

I created two manipulation techniques for the first user study:

1. One-Handed manipulation technique (OH): (This technique is similar to 6DOF manipulation based on the Bat [6]) the user uses one hand to hold a buttonball which has a corresponding 3D spherical cursor in the virtual environment (Figure 5.2). For translation and rotation, the user presses and holds the selection button after placing the cursor inside the target box. Then the box movement is attached to the cursor with the cursor center as the rotation center. Additionally, for visual feedback, I display a circle indicating enabling of rotation and four arrows indicating enabling of translation as shown below.

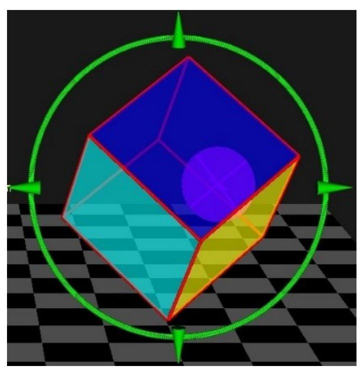

Figure 5.2 Visual feedback of OH technique with the target box being selected

2. One-Handed manipulation with separate translation and rotation (OHS): this mode only allows translation or rotation separately. Users need to use their non-dominant hand to click the space button on the keyboard for the switching between translation and rotation mode. Figure 5.3 illustrates corresponding visual feedback when translation or rotation is enabled. In the translation mode, the rotation of the button ball will not cause the box rotation. In the rotation mode, the relocation of the button ball will not cause the translation of the target box.

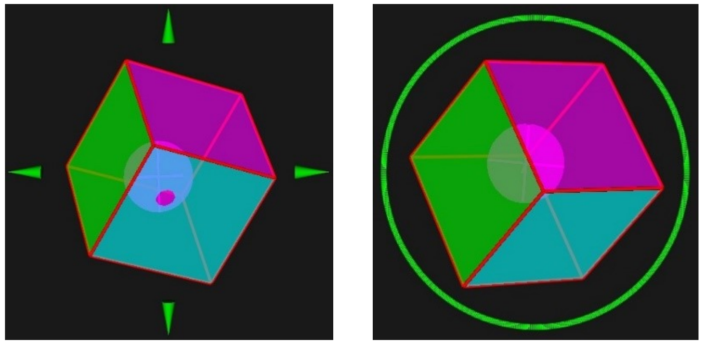

Figure 5.3 Visual feedback of OHS technique when translation is enabled (left) and rotation is enabled (right) at different times

The design of these two techniques, OH and OHS, has several purposes. The user's button-ball motion during OH will be analyzed to track the degree to which translation and rotation are integrated (via the m-Metric), and to determine if the degree of integration changes between the ballistic versus control phases. Second, OHS will test if forcing the user to separate rotation from translation is be beneficial during either phase as compared to OH.

5.2.1 Ghost Cursor Design

For each manipulation technique, for each user at the start of her session, the user holds the button ball and rests her elbows on the chair's arms and the experimenter sets a translational offset that places the 3D cursor in the center of the screen. This is designed to maximize the degree to which the user rests her elbows during interaction [26]. This offset maintains a constant value throughout the experiment and is referred to as the initial offset.

For the OHS technique, the DOF separation raises a problem for the fixed offset. When OHS is in rotation mode, the selected box should not translate. However, when the user rotates the button ball, it nearly always moves as well. If the cursor offset remains fixed, the cursor would often move outside the selected box during rotations. To be visually consistent with the OH condition, the cursor should stay within the selected box. Hence we want to essentially freeze the cursor location during rotation mode. But this implies the button-ball to cursor offset is changed. When the user switches back to translation mode, the question arises should the cursor jump to its standard location (based on the fixed offset) or does the cursor maintain its position causing the button-ball offset to be permanently altered? We tried several methods to manage this issue:

1. Use a second button on the button ball to reset the cursor offset to the initial offset. Hence, if after a rotation mode operation, the user feels the changed offset is making further operations uncomfortable, she can reset the offset.

2. Provide an additional way of mode switching. An additional key on the keyboard ('B') can be used to switch between translation and rotation mode. If this key is used to switch modes, when switching from rotation to translation mode, the offset is reset. (Switching modes using the space bar leads to behavior described earlier, which generally causes leaves the offset altered when switching from rotation back to translation mode).

3. Dual cursors I: When rotation mode is engaged, a translucent gray "ghost" cursor appears coincident with the standard cursor. The ghost cursor freezes at this position (within the selected box) while the regular cursor continues to move with the button ball. Then when the user releases the selection button on the button ball, the ghost cursor disappears. The assumption is during rotation mode the user will visually attend to the ghost cursor and the box, and when she releases the button, she will again attend to the regular cursor.

4. Dual cursors II: When rotation mode is engaged, a translucent gray "ghost" cursor appears coincident with the standard cursor (Figure 5.4). The original cursor stays at its current position, while the ghost cursor continues to move with the button ball. Then when the user releases the selection button, the 3D cursor jumps to and overlaps its ghost cursor, which then disappears.

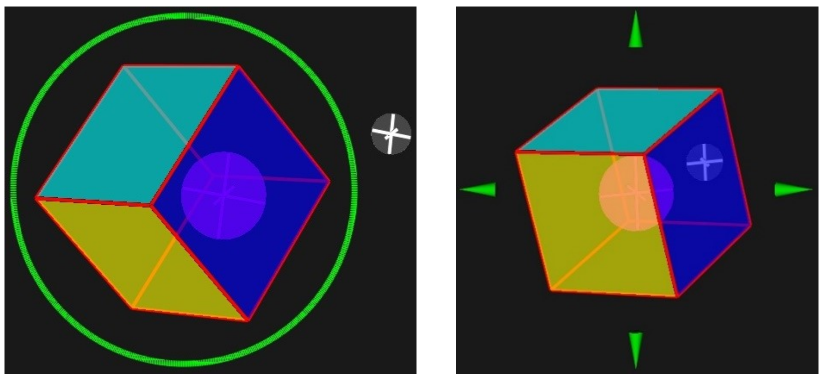

Figure 5.4 Ghost cursor design. Left: In rotation mode, ghost cursor (gray) left the main selection cursor (spherical cursor inside the box) and moved outside the box. Right: the ghost cursor stays separately with the main cursor if the selection button is not released.

Informal pilot testing found Method 1 increased the docking completion time by interrupting continuous operation when switching between modes. Method 3 and 4 were found to be more flexible and intuitive than Method 2. Finally, Method 4 appears more consistent with the OH technique since in both cases the user visually attends to the original cursor during rotation. Therefore, Method 4 was adopted for the OHS technique.

As a further refinement, if the user does not release the selection button while switching modes, the 3D cursor remains attached to the box. This avoids the user having to perform a re-selection during a rotation-to-translate mode switch, even if the ghost cursor has moved outside of the selected box. Finally, the offset is always reset when a docking trial is completed.

5.2.2 3 Matching Tolerances Design

Since users' behavior and performance may differ in different matching tolerances, I set three different matching conditions for the docking test: 0.84cm/2 (fine), 0.84cm (medium), 0.84cm*2 (coarse) (Figure 5.5). I inform the user about the current docking threshold by drawing two spheres on two diagonal box corners with the radius equal to the docking tolerance.

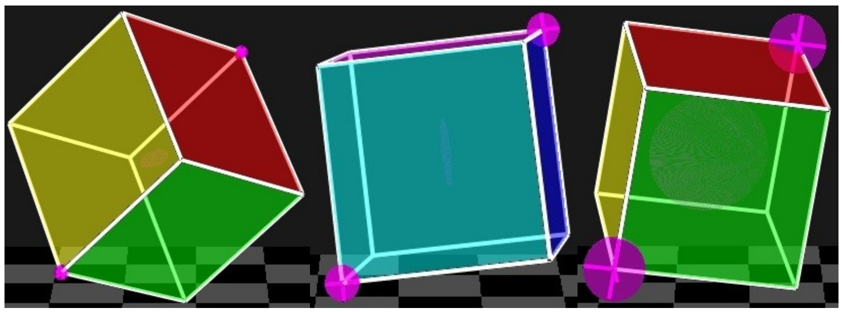

Figure 5.5 Visual feedback indicating three levels of tolerances (from left to right: 0.84cm/2 (fine), 0.84cm (medium), 0.84cm*2 (coarse))

5.2.3 Overall Design

This experiment is a 2 by 3 design with two interaction techniques and three levels of tolerance. There were 30 trials for each technique per tolerance condition. The total experiment time for each user was around 1.5 hours.

The experiment set up was similar to that described in Chapter 3 [15] but the user only used one button ball held in her dominant hand. The virtual environment was also similar as that in Chapter 3 but with only one target box for each trial and also the box size was the same as the docking box located at the center of the scene (Figure 5.6).

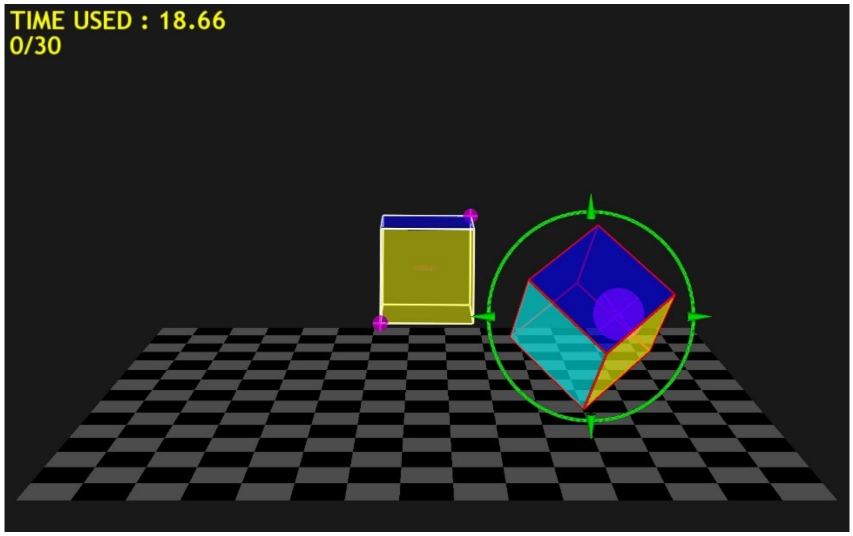

Figure 5.6 Virtual Environment for the user study (OH technique)

For each technique, the program recorded the location, angle, central distance and time stamp at 15HZ and the docking completion time for each trial.

5.3 Experiment 1: Hypotheses

The hypotheses for the Experiment 1 are (based on investigator's observation for OH technique in Chapter 3):

H1: For the OH technique, in the ballistic matching phase, users will have more separated control of translation and rotation compared with the control phase. This means the m-Metric value for translation rotation couple should be lower in ballistic phase compared that in the control phase. (Since separate control may be simpler to control translation and rotation in a sequence compared to managing the orientation and location of the target at the same time.)

H2: In the ballistic phase, OHS would have a faster completion time compared with OH technique since users may find it easier to control.

H3: In the control phase, OH would have a faster completion time compared with OHS (Because according investigator's observation in the user study, Chapter 3, when the target box was close to the docking box, it became hard for the users to judge if should adjust location or orientation to for the final matching relying on the visual feedback. Thus, users often tune the 6DOF pose with integral manner observing if the alignment of boxes became better).

H4: The EFF value of the control phase would be larger than ballistic phase since the precise tuning movement may require multiple back and forth adjustments.

H5: For the total docking completion time, OH would have a faster completion time compared with OHS technique under the small and medium tolerance.

5.4 Experiment 1: User Study

The virtual environment is displayed in a stereoscopic, Fish-tank VR configuration. The environment has a checker-board ground-plane. It is 40 cm square with half appearing behind the display surface and half appearing in front. In the center of the screen is a translucent box, the Objective Box, of fixed size and at a random orientation per trial. Each face has a different color. This cube's pose remains stationary relative to the display screen during target box manipulation. At each trial, a target box with the same size of the objective box appear at random locations and orientations on the ground-plane. The user must select the target box and align the target cube with the objective cube. Like colored faces must match. This requires object rotation and translation.

When the distance between the target cube's corresponding vertices is within a tolerance (0.42 cm, 0.84 cm or 1.68 cm) of the objective cube's vertices, the frame of the cube turns green. If the target box is selected and kept green for 0.8 seconds [25], it will disappear and a success sound will be played indicating one docking operation is complete. Next, the system automatically generates a new target box for the next trial.

Once for each user (at the start of her session), the user holds the button balls and rests her elbows on the chair's arms and the experimenter sets a translational offset that places the 3D cursors in the center of the screen. This is designed to maximize the degree to which the user rests her elbows during interaction.

Each participant spent roughly 1.5 hrs for the user study. Before the formal docking test of each manipulation technique, each participant had roughly 5 minutes training. Next, for each technique, an experiment block required a participant to finish 30 docking task trials. The study had 12 participants.

5.5 Experiment 1: Data Analysis

We measure the docking completion time of the target box per trial. The completion time is measured from the point when the user begins the object selection to the point when the selected object disappears in the scene. Also the program recorded the manipulation time which is the time spent subtracting the selection time. Also, for each docking trial, we divide the completion time into two parts: coarse docking time (ballistic phase) and precise adjustment time (control phase). The watershed is decided by the same rule (Figure 4.8) described in Chapter 4. Moreover, we recorded the target box pose information at 15 HZ rate for each docking test.

For the 0.42 OH case, we calculated the m-Metric value for each trial and also listed the m-Metric component SOC and EFF for analysis. (Since the final stage of the docking operation in the fine tolerance level requires more precise control; compared with OHS, only OH has the possible integral control.) Moreover, each of these values are calculated for the whole docking process, as well as ballistic phase and control phase separately.

5.5.1 Quantitative

For the total completion time as the dependent variable, in the sample of 12 participants, an analysis of variance was performed on the 2x3 multi-factor design, with threshold levels (fine (0.42), medium (0.84), coarse (1.68)) and manipulation techniques (OH and OHS) as independent variables. The analysis revealed:

- A significant interaction effect: F (2, 22) = 7.19, p =.004, partial eta2 = .40
- A significant main effect for Task threshold levels, F (2, 22) = 32.21, p <.001, partial eta2=.74
- A significant main effect for Manipulation Technique, F (1, 11) = 122.07, p<.001, partial eta2= .92.

A post hoc test showed that there was a significant difference among small tolerance (M = 26.25, SE = 2.69), medium tolerance (M = 16.11, SE = 1.71) and coarse tolerance (M = 11.66, SE = .75). To interpret the first interaction, simple effects tests were computed for "tolerance level". It indicated that there were significant differences among 3 manipulation techniques for each tolerance level (Figure 5.7).

- For fine tolerance: p< .001, (OH M = 20.45, SD = 8.71, n = 12; OHS M = 32.04, SD = 10.24, n = 12)
- For medium tolerance: p< .001, (OH M = 12.09, SD = 4.71, n = 12; OHS M = 20.12, SD = 7.77, n = 12)

- For coarse tolerance $p < .001$, (OH M = 8.54, SD = 1.72, n = 12; OHS M = 14.77, SD = 3.76, n = 12).

Thus, we can conclude that for each tolerance, OH had faster completion time compared with OHS. This confirms H5: OH is faster than OHS at small and medium tolerances, but we had expected similar completion times for the coarse tolerance condition, and instead OH was faster.

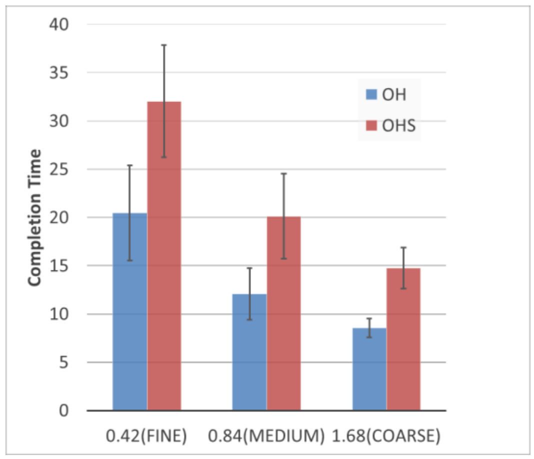

Figure 5.7 The completion time with two techniques and 3 tolerances. Bars show 95% confidence intervals.

Somewhat expected due to the OHS technique design, I observed during the user study, the OHS manipulation required more frequent re-selection than OH due to the ghost-cursor mechanism when switching from rotation mode to translation mode. Thus, I analyzed the manipulation time (total docking time - selection time) for each technique. The analysis revealed a significant main effect for Manipulation Technique, $F(1, 11) = 126.50$, $p<.001$, partial eta2= .92. The following simple effects were significant:

- For fine tolerance: $p < .001$, (OH M = 16.48, SD = 7.72; OHS M = 24.43, SD = 7.56)

- For medium tolerance: p< .001, (OH M = 8.95, SD = 3.63; OHS M = 14.76, SD = 5.41)
- For coarse tolerance p< .001, (OH M = 6.01, SD = 1.40; OHS M = 10.48, SD = 3.10)

Thus, we can conclude that for each tolerance level, even without considering the selection time, OH had shorter manipulation time compared with OHS. Hence even after subtracting any additional time caused by the ghost cursor re-selection, OH is still faster.

For each tolerance level, we calculated completion time difference between the two techniques (OHS-OH), shown in Figure 5.8A. An analysis of variance performed on these data revealed a significant effect due to tolerance level, F (2, 22) = 7.19, p=.004, eta2 = .40. Multiple comparison tests (p=.05), indicated that the difference for the standard tolerance (M= 8.03, SD=4.90) and large tolerance (M=6.23, SD=2.69) were not significantly different. Both of these difference are differ significantly from the small tolerance difference (M=11.59, SD=3.93). This result implies that for the small tolerance, the benefit of integral control of translation and rotation became larger.

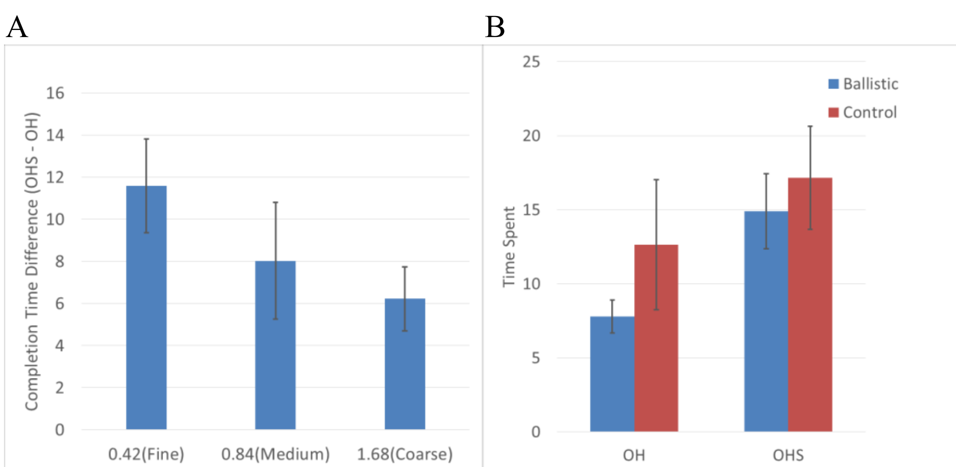

Figure 5.8 Completion time differences between OHS and OH techniques in three tolerance levels (A); Control time and ballistic time of OH technique in fine tolerance condition (B). Bars show 95% confidence intervals.

For the OH technique in 0.42 (fine) tolerance condition, the total completion time was divided in to two parts (because this condition potentially contains more precise manipulation compared to other two larger tolerance conditions): ballistic phase time and control phase time (Figure 5.8B). For matched-t test with p=.05, 2-tailed, the comparison for ballistic phase time revealed a reliable difference between the two techniques. The sample mean with OH has shorter ballistic phase time (M = 7.80, SD = 1.96, n =12) than the OHS technique (M = 14.89, SD = 4.49, n = 12), t (11) < .001. Also, for the control phase, the sample mean with OH has shorter control phase time (M = 12.65, SD = 7.76, n =12) than the OHS technique (M = 17.15, SD = 6.15, n = 12), t (11) = .003. Thus, we could conclude that OH technique was significantly faster than OHS technique in both ballistic phase (contradicting H2) and control phase (confirming H3).

For OH technique we also calculated the 0.42 OH condition m-Metric values for the total docking process, ballistic phase and control phase.

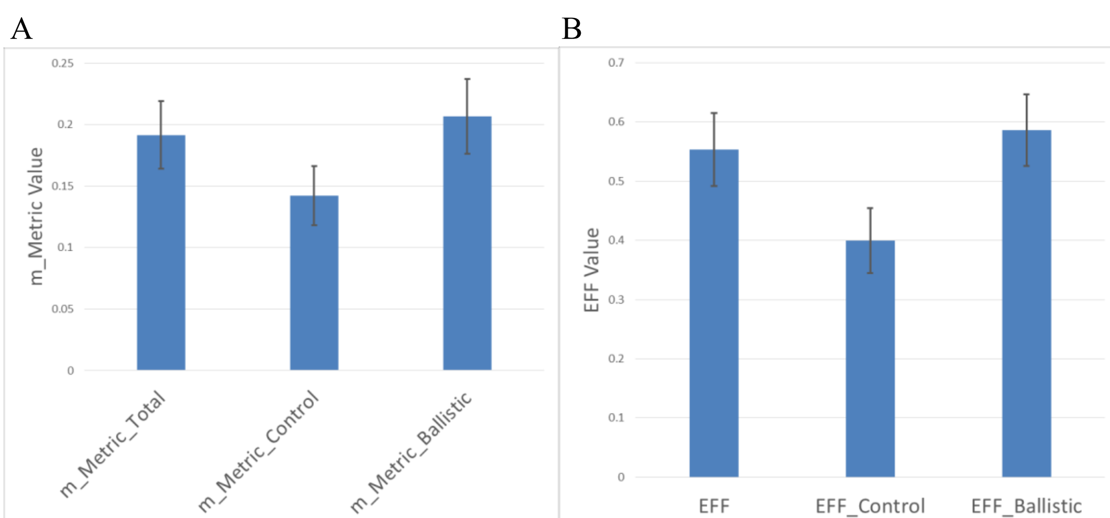

Figure 5.9 The sample means of m-metric value for total docking test, control phase and ballistic phase (A); The EFF values of total docking period, control phase and ballistic phase for OH technique in fine tolerance condition (B). Bars show 95% confidence intervals.

An analysis of variance performed on these data revealed a significant effect of phase on m-Metric values, $F (2, 22) = 30.49$, $p <.001$, eta2 = .74. The eta^2 indicates a large effect. Multiple comparison tests (p=.05), indicated that in the control phase m-Metric value (M= .14, SD=.05) is significantly lower than that of ballistic phase (M=.21, SD=.54) and the whole docking process (M=.19, SD=.05) (Figure 5.9 A). Further, the whole process m-Metric was significantly lower than that of the ballistic phase (Figure 5.9A). The result revealed that for control phase, translation and rotation operations were more separated than the ballistic phase which contradicted H1. Moreover, the EFF values revealed the control phase path efficiency (M=.39, SD=.10) is significantly less than the average (M=.55, SD=.11) and ballistic phase (M=.59, SD=.11) (Figure 5.9 B). This confirmed H4.

5.5.2 Qualitative

The post questionnaire (APPENDIX D/Post-Questionnaires 1) asked which technique the user preferred for translation, rotation and overall (Table 3). Most participants preferred OH technique and agreed that OH was better for rotation and translation control. For rotation, OH was rated better for rotation than OHS. A plausible explanation is that in OHS when a user tries to rotate, their hand also will perform some translation; while the ghost cursor helps visually represents the discrepancy, the mapping between the button ball and the virtual object is still direct than with OH.

Table 3 Qualitative result for OH, OHS comparison. Individual participant preferences are labelled S1 through S12.

	Rotation	Translation	Preferred Most
OH	(9) S1 S2 S3 S4 S5 S6 S8 S10 S11	(6) S1 S4 S5 S6 S7 S10	(9) S1 S2 S3 S4 S5 S6 S8 S10 S11
OHS	(3) S7 S9 S12	(6) S2 S3 S8 S9 S11 S12	(3) S7 S9 S12

5.6 Experiment 1: Discussion

Our result revealed that for both small and large tolerances (i.e. manipulation required high or coarse precision) OH outperform OHS. Moreover, in both ballistic and control phases, OH outperformed OHS. This means the OH technique which has a match between control structure and perceptual structure worked better than OHS technique which does not have this match. This result complied with Jacob's and contradicted with other researchers who argue for separating translation and rotation control to reduce unwanted manipulation. The result also showed a tighter tolerance requirement lead to more separated rotation and translation control. However, even though in all cases, the low m-Metric value indicated that users control translation and rotation separately most of the time, it also indicated the small portion of integral control played an important role, leading to OH outperforming OHS.

Because for each manipulation phase (ballistic phase and control phase), the OH technique outperformed OHS technique, there is no need to explore developing a technique which automatically switches between integral and separate controls as I suggested in 5.1.

5.7 Experiment 2

For Experiment 2, we explored the role of separate and integral control of DOFs in to a higher DOF manipulation situation, which adds scaling control into consideration yielding 7DOF (6DOF pose + 1DOF scaling). This experiment is a extends Experiment 1 with the purpose of evaluating if separate or integral control of pose and scaling benefit ballistic phase (coarse matching) and control phase (precise matching) during a 7DOF docking task.

5.7.1 Experiment 2: Experiment Design

Experiment 2 could also be considered as an extension of Jacob's experiment on 2D location/size task [31] which revealed integral scaling and translation will outperform separate scaling and translation during the final fine tuning stage (control phase).

We use three 7DOF manipulation techniques described below:

1. One-Handed pose with Separate Scaling (OHSS) – the non-dominant hand button ball controls pose when a non-dominant ball button is held and non-dominant cursor is inside a target box. Holding a second button on the dominant buttonball enables two-handed scaling. When the scaling is enabled, pose control is disabled. Note, however, the user must still hold down both the dominant ball button and the non-dominant ball button to enable scale mode.

2. One-Handed pose with Integral Scaling (OHIS) – As with OHSS, non-dominant buttonball controls pose while dominant buttonball controls two-handed scaling. However, the pose and scaling control always enabled together. As with OHSS, the box

selection occurs when the non-dominant button is pressed, but to maintain a consistency in the number of button presses required, pose will not be enabled until the dominant button is pressed and held as well, which also enables scale.

3. One-Handed pose with Integral or Separable Scaling (OHISS) – (This technique has the same control as the OTS technique in Chapter 3.) The non-dominant ball controls pose; the dominant ball does two-hand scaling. Pressing the non-dominant ball button alone enables pose (6DOF). Holding down the dominant ball button, as well, then further two-hand scaling; so all 7DOF are enabled at once.

In each technique, scale-mode displays a dotted green line between the two cursors (Figure 5.10 A) as in Chapter 3.

For the OHSS technique, the target box should not move when the scaling is enabled, this it introduces a similar cursor offset problem as discussed in the OHS technique for Experiment 1. Therefore in OHSS, when the scaling is enabled, the non-dominant cursor (Figure 5.10 B: purple cursor inside the target box) stays with the selected box and a translucent grey ghost cursor represents the cursor location at the initial fixed offset from the non-dominant button ball. If only the dominant button is released, the purple cursor and its ghost cursor stay at their locations relative to the target box, 6DOF pose control is enabled, and the center of rotation remains with the purple cursor. If the user releases the non-dominant button, all control is disabled, the target box is deselected, and the non-dominant cursor jumps to its ghost cursor location.

A B

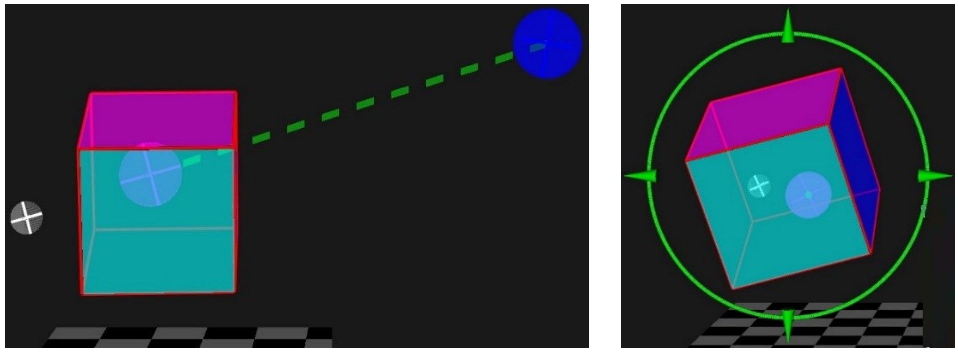

Figure 5.10 OHSS technique visual feedback in translation mode with ghost cursor (A) and pose control mode (B)

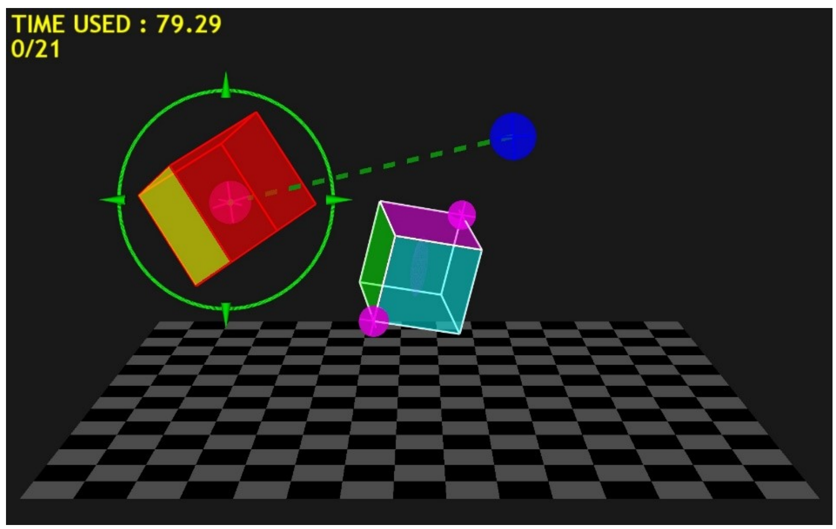

Figure 5.11 OHIS technique visual feedback and the docking experiment environment

Same as in Experiment 1, there were 3 tolerance levels with two spheres located at corners of docking box to indicate the level. Target boxes with different sizes were used in this experiment: 50% sized box, 100% sized box and 200% sized box. At each trial, a target box appeared at random location and orientation on the ground-plane. For every 3 trials, the different sized box appeared once in randomized order. The user must select the target box and align the target with the objective box (Figure 5.11).

5.7.2 Experiment 2: Hypothesis and User Study

Eighteen unpaid students from the Computer Science, Mechanical Engineering and Architecture departments with little or no experience using 3D computer graphic applications participated in the study. Participants were required to tell the distance differences of different boxes in the scene and distinguish the colors of the box frames and faces when wearing stereo glasses. There were 3 (tolerance levels) X 3 (manipulation techniques) = 9 manipulation conditions for each participant. Each conditional had 21 docking trials including 3 different box sizes. The presentation order for 9 conditions to the participants was counter balanced by using the Latin square. Including pre-questionnaire and post- questionnaire, each participants took about 2 hours for this user study.

We have the following hypotheses (based on investigator's observation for OTS technique in Chapter 3):

H1. For the coarse tolerance condition, no significant difference will occur among the three manipulation techniques because of a floor effect, i.e. the coarse tolerance condition is so "easy" that OHIS and OHISS will show no benefit. For the fine tolerance condition, OHIS and OHISS would outperform OHSS. This is expected because the user study in Chapter 3 observed that many users enabled the 7DOF control in the final tuning stage which indicated that operations requiring higher precision control may need integral control of different DOFs.

H2. In ballistic phase, no significant difference among the three techniques is expected because the ballistic phase does not need precise control so OHIS and OHISS will show no benefit. In control phase, where precise control matters, OHISS will outperform OHIS which will outperform OHSS.

H3. OHISS will have significant less physical fatigue compared with the other two. Compared to OHIS, OHISS does not force both hands to be simultaneously controlled. Compared to OHSS, OHISS requires less overall arm motion.

H4. The overall ratings for OHISS would be higher than the other two techniques since it provides more optional control for the users.

5.7.3 Experiment 2: Data Analysis

In a sample of (n=18) participants, an analysis of variance was performed on the 3 x 3 x 3 multi-factor repeated measures design, with manipulation techniques (One-Handed with integrated or separable scaling (OHISS), One-Handed with integral scaling (OHIS) and One-Handed with separate scaling (OHSS)), level of tolerance (fine, medium and coarse) and target box size (50%, 100% and 200%) as the independent variables, and box docking completion time as the dependent variable. The analysis showed:

- No significant interaction effect between manipulation technique and box size, $F(4, 68) = 1.69$, $p = .16$, partial eta2 = .09, and
- A significant interaction effect between manipulation technique and tolerance, $F(4, 68) = 3.50$, $p = .01$, partial eta2 = .17. (The data does not meet the sphericity assumption, but the corrected test (Greenhouse – Geisser) showed the same results.).

The analysis also showed:

- A significant main effect for manipulation technique, $F(2, 34) = 10.23$, $p < .001$, partial eta2=.38.
- A significant main effect for tolerance, $F(2, 34) = 94.77$, $p < .001$, partial eta2= .85.

- A significant main effect for box size, F (2, 34) = 14.17, p<.001, partial eta2= .46.

Observation 1: A post hoc test revealed that for manipulation technique (Figure 5.12 A), there was no significant difference between OHISS (M = 16.79, SE = .91) and OHSS (M = 18.53, SE = 1.06). But both of them had significantly less completion time than OHIS (M = 21.30, SE = 1.37). This demonstrated separated scaling control outperformed integrated scaling control in this docking experiment.

For tolerance, the fine tolerance has significant longer completion time (M = 29.31, SE = 1.87) than medium tolerance (M = 15.65, SE = .88) which has significant longer completion time than that of coarse tolerance (M = 11.66, SE = .59).

For box size (Figure 5.12 B), there was no significant difference between 50% (M = 20.46, SE = 1.12) and 200% box (M = 20.30, SE = 1.24) sizes. However, they both had significant longer completion time than that of 100% box size (M = 15.86, SE = .99).

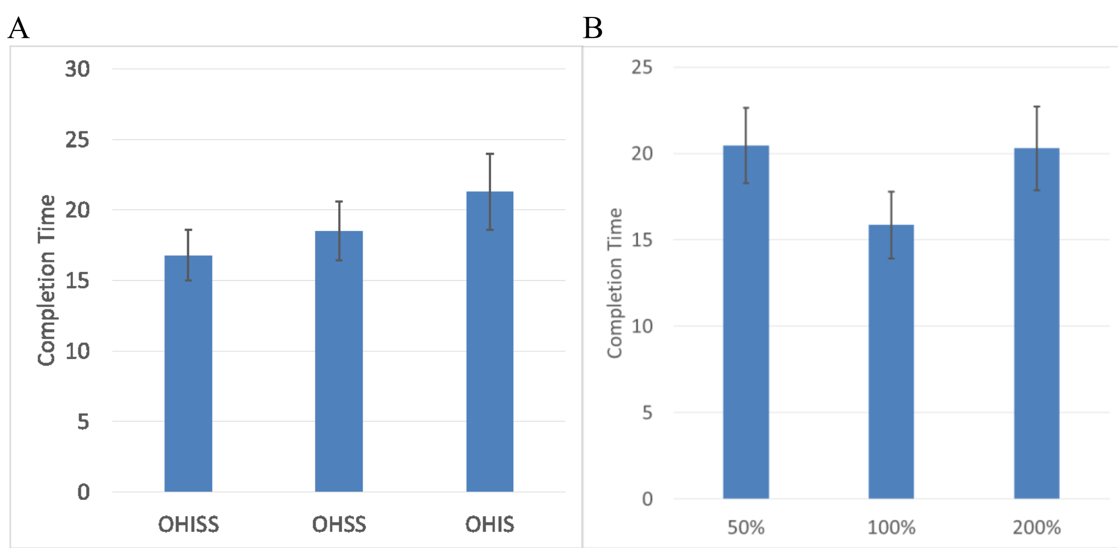

Figure 5.12 Completion time with different manipulation techniques (A); Completion time in different box sizes (B). Bars show 95% confidence intervals.

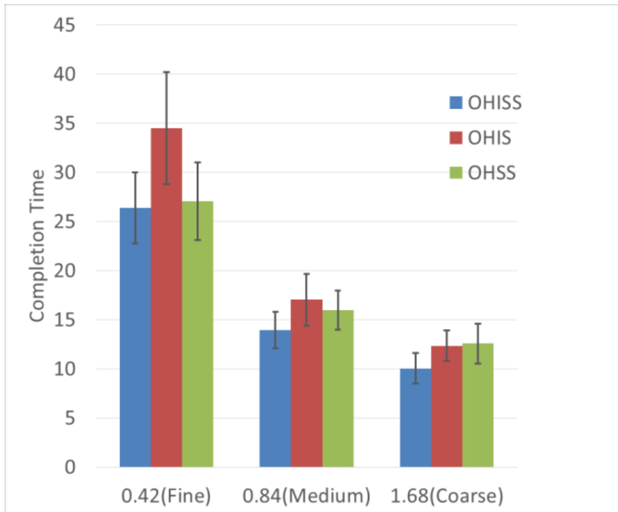

Figure 5.13 Completion time of 3 manipulation techniques in 3 levels of tolerances. Bars show 95% confidence intervals.

To interpret the interaction, simple effects were computed for tolerance (Figure 5.13). It indicated that there was no significant difference between OHIS and OHSS for the coarse tolerance, but OHISS has significant less completion time than OHSS (OHISS M = 10.05, SD = .80, n = 18; OHIS M = 12.35, SD = .80, n = 18; OHSS M = 12.56, SD = 1.04, n = 18). For medium tolerance, there is no significant difference between OHISS and OHSS, but they both have significantly less completion time than OHIS (OHISS M = 13.92, SD = .95, n = 18; OHIS M = 17.03, SD = 1.35, n = 18; OHSS M = 16.00, SD = 1.02, n = 18). For fine tolerance, there is no significant difference between OHISS and OHSS, but they both have significantly less completion time than OHIS (OHISS M = 26.39, SD = 1.85, n = 18; OHIS M = 34.51, SD = 2.92, n = 18; OHSS M = 27.03, SD = 2.02, n = 18). This indicates when fine and medium tolerance is required, OHSS outperformed OHIS.

Observation 2: But when coarse tolerance is sufficient, OHSS and OHIS do not differ from each other, but OHISS performed significantly better OHSS. This suggests that a technique providing only separate scaling control should be avoided.

Only the fine tolerance condition contains a control phase which requires precise matching control at the final docking stage. Therefore, in the fine tolerance condition, we divide the whole docking period into two parts: ballistic phase and control phase (Figure 5.14). An analysis of variance was performed on the 3 x 3 multi-factor repeated measures design, with three manipulation techniques and three target box sizes as the independent variables, and box ballistic time or control time as the dependent variable.

For the ballistic time (Figure 5.14A), the analysis showed significant interaction effect between manipulation technique and box size, F (4, 68) = 2.78, p =.03, partial eta2 = .14. The analysis also shows a significant main effect for manipulation technique, F (2, 34) = 6.81, p =.003, partial eta2=.29 and a significant main effect for box size, F (2, 34) = 7.63, p=.002, partial eta2= .31. A post hoc test showed that for manipulation technique, there was no significant difference between OHISS (M = 18.17, SE = 1.22) and OHSS (M = 19.13, SE = 1.28). But both of them have significantly less ballistic time than OHIS (M = 23.46, SE = 1.84).

Observation 3: These results indicate that for a fine tolerance, during the ballistic phase, to reduce completion time we should provide the user with separable scaling control (OHISS or OHSS) rather than integral scaling control (OHIS). Note, that fine tolerance-ballistic phase has the same watershed threshold as the coarse tolerance condition. So both fine tolerance-ballistic phase and the coarse tolerance condition require only low precision operation. One might have expected similar performance rankings of the 3 techniques. However, in the coarse tolerance condition, OHISS performed significantly better than OHSS and OHSS did not differ from OHIS. This suggests participants' behavior somewhat differs depending on the desired final tolerance and their goals.

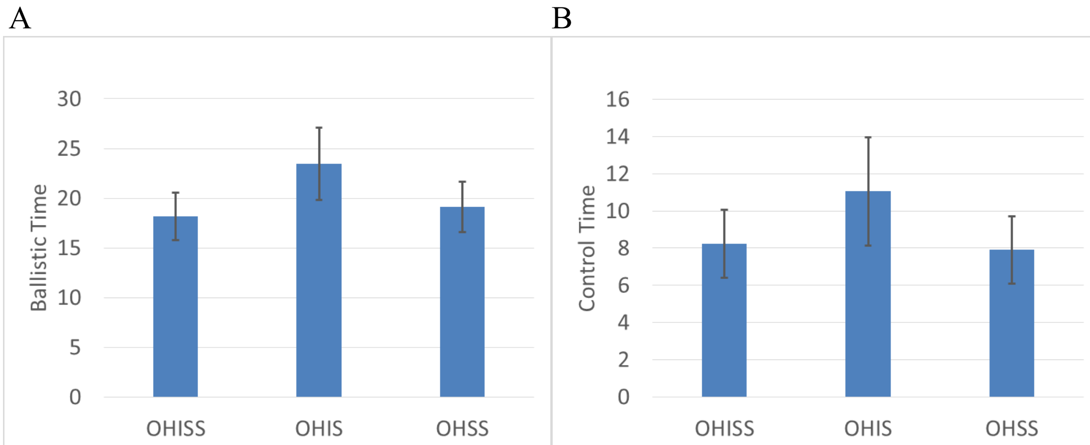

Figure 5.14 In OHIS technique and fine tolerance condition: ballistic time of different manipulation techniques (left); control time of different manipulation techniques (right). Bars show 95% confidence intervals.

For the control phrase (Figure 5.14B), the analysis showed no significant interaction effect between manipulation technique and box size, F (4, 68) = .30, p =.88, partial eta2 = .02. The analysis showed a significant main effect for manipulation technique, F (2, 34) = 3.48, p =.04, partial eta2=.17 and no significant main effect for box size, F (2, 34) = .37, p =.69, partial eta2= .02. A post hoc test showed that for manipulation technique, there was no significant difference between OHISS (M = 8.23, SE = .94) and OHSS (M = 7.91, SE = .92). There was also no significant difference between OHISS and OHIS (M = 11.05, SE = 1.48).

<u>Observation 4:</u> But OHSS has significantly less control time than OHIS. This indicated that for fine tolerance, during the control phase, to reduce completion time, we should not force the user to use integral scaling control (OHIS).

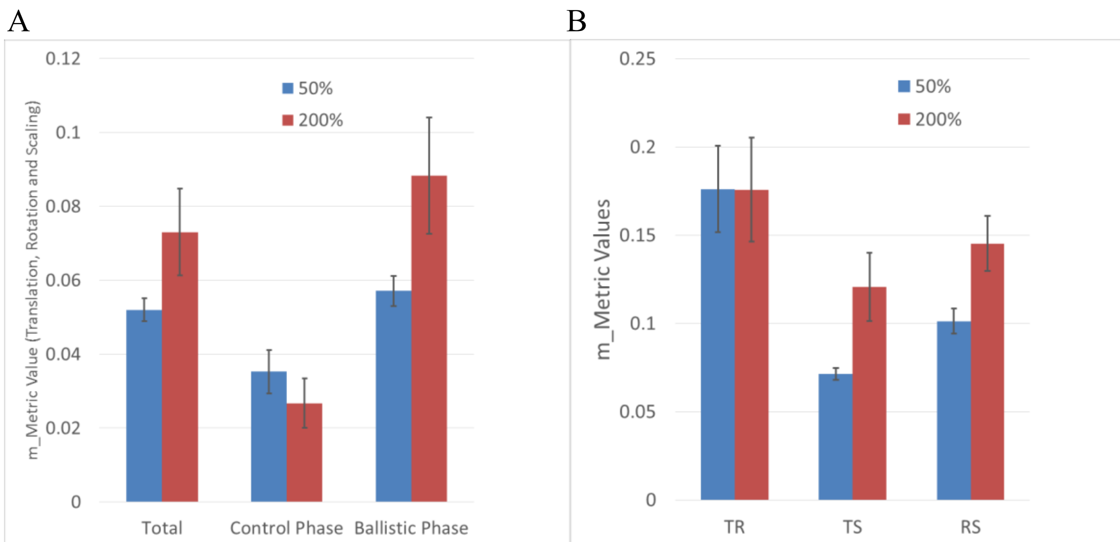

Figure 5.15 For OHIS technique in fine tolerance level: the m_Metric values in different manipulation phases (left); m_Metric values of different DOF couples. Bars show 95% confidence intervals.

For One-Handed with Integral Scaling (OHIS) in the fine tolerance condition, an analysis of variance was performed on the 3 x 2 multi-factor repeated measures design, with three different m-Metric measure periods, measured over: the total docking period (DP), the control phase (CP) and ballistic phase (BP) (Figure 5.15 A). Target box size (50% and 200%) is the second independent variable. (100% box size is not considered here since scaling was not required during its manipulation). The dependent variable is m-Metric values of translation, rotation and scaling. The analysis showed significant interaction effect different m-Metric measures and box size, $F(2, 34) = 22.70$, $p < .001$, partial eta2 = .57. The analysis also showed a significant main effect for different m-Metric measure periods, $F(2, 34) = 97.60$, $p < .001$, partial eta2=.85 and a significant main effect for box size, F (1, 17) = 9.42, p=.007, partial eta2= .36. A post hoc test shows that for different m-Metric measure periods, m-Metric of DP (M = .06, SE = .003) is significantly higher than that of CP (M = .03, SE = .002) and significantly lower than that of BP (M = .07, SE = .004). For box size, m-Metric value of 50% (M = .05, SE = .002) is significantly lower than that of 200% box (M = .06, SE = .005).

Observation 5: This illustrated in that ballistic phase, translation, rotation and scaling occur more in cooperated control than they do on average during the total docking period; in control phase, these three operations occur more in separated control than they do on average during the entire docking period.

For One-Handed with integral scaling (OHIS) in fine tolerance condition, an analysis of variance was performed on the 3 x 2 multi-factor repeated measures design, with three different m-Metric coupling measures: translation-rotation coupling (TR), translation-scaling coupling (TS) and rotation-scaling coupling (RS) (Figure 5.15B). Target box size (50% and 200%) is the second independent variable. The dependent variable is the m-Metric value. The analysis showed significant interaction effect between different m-Metric coupling measures and box size: F (2, 34) = 15.24, p <.001, partial eta2 = .47. The analysis also showed a significant main effect for different m-Metric coupling measures, F (2, 34) = 60.09, p <.001, partial eta2=.78 and a significant main effect for box size, F (1, 17) = 14.70, p=.001, partial eta2= .46.

Observation 6: A post hoc test showed that for different m-Metric coupling measures, m-Metric of TR (M = .18, SE = .01) was significantly higher than that of RS (M = .12, SE = .005) which was significantly higher TS (M = .10, SE = .005). This result revealed that whereas rotation and translation seem simultaneous, scaling proceeded more independently.

To interpret the interaction, simple effects were examined. They indicate that there is no significant difference between different box size for the TR m-Metric value (50% M = .18, SD = .05, n = 18; 200% M = .18, SD = .06, n = 18). For TS m-Metric value, 50% box size has significant lower m-Metric value than that of 200% box size (50% M = .07, SD = .007, n = 18; 200% M = .12, SD = .004, n = 18). For RS m-Metric value, 50% box size has significant lower m-Metric value than that of 200% box size (50% M = .10, SD = .02, n = 18; 200% M = .15, SD = .03, n = 18).

<u>Observation 7:</u> Thus, scaling up the 50% box size and scaling down the 200% sized box performed differently with scaling up having greater separation of scaling and pose control (RS, TS) than when scaling down. Not surprisingly, the TR value is not affected by the presence/absence of required scale adjustment (100% vs 50%, 200%) nor the direction of scale adjustment (50% vs 200%).

<u>Observation 8:</u> When asked which technique was better for overall performance (APPENDIX D/Post-Questionnaires 2), ten participants answered OHISS, six answered OHSS, and three answered OHIS. When asked which interaction technique was better for scaling ten participants answered OHISS, seven answered OHSS and one answered OHIS. When asked which technique was the most intuitive, eleven answered OHISS, four answered OHSS and three answered OHIS (Table 4).

<u>Observation 9:</u> Participants rated arm fatigue after finishing the experiment for each interaction condition (on a 7-point Likert scale, 1 no fatigue to 7 very painful). There was significant main effect for manipulation technique, $F(2, 34) = 3.40$, $p = .045$,

partial eta2=.17. A post hoc test showed arm fatigue was not significantly different between OHSS (M = 3.39, SE = .34) and OHISS (M = 2.89, SE = .27). However, OHISS had significantly lower fatigue rating than OHIS (M = 4.06, SE = .39).

Table 4 Qualitative result for OHSS, OHIS and OHISS comparison. Individual participant preferences are labelled S1 through S18.

	Scaling	**7DOF Control**	**Intuitiveness**
OHSS	(7) S1 S3 S6 S10 S11 S12 S13	(4) S2 S10 S11 S14	(4) S3 S10 S11 S12
OHIS	(1) S9	(1) S9	(2) S2 S9
OHISS	(10) S2 S4 S5 S7 S8 S14 S15 S16 S17 S18	(13) S1 S3 S4 S5 S6 S7 S8 S12 S13 S15 S16 S17 S18	(12) S1 S4 S5 S6 S7 S8 S13 S14 S15 S16 S17 S18

5.7.4 Experiment 2: Discussion

According to the analysis, we conclude that for coarse tolerance and ballistic manipulation, there was no significant difference between separate scaling and integral scaling control (Observation 2, Observation 3). Separable scaling outperformed either of the two in different cases. Moreover, integral/separable scaling control (OHISS) could be better than totally separate (OHSS) or totally integral control (OHIS) according to users' preference and arm fatigue feedback (Observation 8, Observation 9). Both in fine tolerance and control phase, separated scaling control (OHSS) outperformed the integral control (OHIS) (Observation 2, Observation 4). Furthermore, even for forced integrated scaling (OHIS), the scaling control was more separated during the control phase than during the ballistic phase (Observation 5). These results suggested for 7DOF manipulation (i.e. pose + scale) (Observation 1) and especially in precise matching operations, separation of scale from pose control can reduce completion time compared to integrating scale and pose.

5.8 Conclusion

Based on the extension of perceptual and control structure in interaction, the rotation and translation control performance (in Chapter 5, Experiment 1) was consistent with Jacob's finding since matching integral control with integral perceptual structure during 6DOF pose (OH) performed better than the non-matching case (OHS). However, scaling in 3D (Experiment 2) contradicts Jacob's 2D location/size experiment result. One would expect that like 2D location and size, the perceptual structure of scaling with 6DOF pose is integral. The control structure of OHIS technique is also integral while the control structure of the OHSS technique is separable. According to Jacob's theory, the OHIS technique, whose integral control structure matches the integral perceptual structure of the 7DOF task, should perform better than OHSS, whose separate control structure does not match the integral perceptual structure of the 7DOF task. But this is not what I found.

Table 5 Technique Comparison (columns are different techniques, rows are control types and related features):

	Translation	Rotation	Scale	Control Integration	Switch Action	Faster Than
OH	isotonic xyz	isotonic rpy		xyz+rpy		> OHS
OHS	isotonic xyz	isotonic rpy		xyz, rpy	modal	
GlobeFish	elastic xyz	isotonic rpy		xyz, rpy	hand motion change	> Spaceball
GlobeMouse	elastic xyz	isotonic rpy		xyz, rpy	re-grip	> Spaceball
Spaceball	isometric xyz	isometric rpy		xyz+rpy		
Multi-touch	isotonic xy	isotonic r	isotonic s			
OHSS	isotonic xyz	isotonic xyz	isotonic s	xyz+rpy, s	modal	
OHIS	isotonic xyz	isotonic xyz	isotonic s	xyz+rpy+s		
OHISS	isotonic xyz	isotonic xyz	isotonic s	xyz+rpy, xyz+rpy+s	modal	

In a previous 2D Multi-touch Interfaces [64], they found that rotation and translation are more integral (measured by the m-Metric) than either scale and translation or scale and rotation. This means that scaling proceeds more independently. Their 2D result is consistent with my 3D 7DOF result.

Masliah et al. [16] studied 6DOF docking and found for 6DOF pose control a low m-Metric value, indicating that most of the time users tend to separate the control of translation and rotation, but there is still a small portion of integral control for all users (i.e. the m-Metric was non-zero). Their experiment, however, did not separately analyze the ballistic and control phrase nor separately analyze separate tolerances. During my similar Experiment 1 (Chapter 5), the control phase m-Metric value was significantly lower than the ballistic phase, which suggests most of the integral control occurs during the ballistic phrase. Further, the integrated technique, OH, improvement over the, separated technique, OHS, is larger for (precise) fine tolerance, than for the medium and coarse tolerances. This also indicates integral control is more important for precise manipulation. Hence, my results refine the observations of Masliah et al. by indicating when integration is important.

The Globefish and GlobeMouse [35] use elastic or isometric translation with isotonic rotation control. Both outperformed integral 6DOF isometric Spacemouse. The authors conclude that:

> "These results also suggest that a 3 DOF + 3 DOF design is better suited for docking tasks than an integrated 1 * 6 DOF-approach. This indicates further that the mental structure of this task is separated with respect to translations and rotations."

Our results do not fit this conclusion. However, the authors are also clear that:

> "[the] unexplored design space for these types of devices is still large. For each DOF, we have the choice of using isotonic, elastic, or isometric input sensors. Some of the DOF could be integrated, others separated."

Hence, the difference in our results from those of [35], suggests that the utility of separating translation and rotation for reducing completion time differs across device types (isometric vs isotonic) and other factors. In their case, separated elastic/isometric translation + isotonic rotation outperform integrated isometric 6DOF. In our case, integrated isotonic 6DOF outperformed separated isotonic 6DOF. However, our separated case (OHS) is modal, the second hand presses a keyboard key to switch between translation and rotation; while in their separated case of GlobeMouse the user changes her grip to switch between translation and rotation. In GlobeFish an explicit grip change is not needed, but it is difficult to make simultaneous controlled rotations and translations—hence rotation and translation are essentially separated.

CHAPTER 6: SUMMARY

6.1 Primary Conclusions and Contributions

Applications in virtual environments, computer aided design, computer aided engineering, scientific data visualization, and many other technologies demand intuitive and reliable object manipulation techniques. Many researchers rely on high DOF input devices or design various variations of current commercial products. Although some of their techniques had relatively better performances in their specific short term experiments, they ignored comfort of long duration usage or feasibility for tasks require frequent precise control. Moreover, some fundamentals such as the benefit of integral or separable DOF control varies in different cases and features such as users' performance varies in various manipulation precision requirements. These subtleties haven't been well explained. The purpose of this thesis is to provide theoretical and empirical basis for the efficient manipulation technique design with practical usability which considers fatigue, device familiarity and acquisition, etc.

The experiment in Chapter 3 explored the efficiency and intuitiveness of several 7DOF manipulation techniques with users' operation preferences. Data analysis showed the advantage of bimanual control (Spindle + Wheel (S+W)) or One-Hand with Two-Hand Scale (OTS)) compared to one-handed control with mode switching (OH). The data showed further that separable scaling control (OTS) could reduce unintended scaling and potentially increase manipulation efficiency. Users' preference also showed OTS which does not always require both hands was preferred over S+W.

Chapter 4 focused on 6DOF manipulation technique design and evaluation based on desktop input devices which have less physical fatigue problems. User study revealed my Trackball+Mouse (TM) technique and SpaceMouse control (isometric 6DOF) outperformed the conventional mouse + keyboard technique. Data analysis showed the TM technique, which is based on isotonic position control, performed better than SpaceMouse which has isometric rate control. Similar to prior work [35], Chapter 4 fatigue ratings of TM versus SpaceMouse suggest that for long duration use desktop support for arms and limbs to rest on and isotonic position control maybe preferable to isometric 6DOF devices.

Chapter 5 performed a more fundamental investigation in two experiments. The isotonic position control choice in these experiments provided the possibility of revealing the original/initial operation habits and user preference in isotonic control. The results revealed that the benefit of integral control vs separate control of DOFs claimed by previous researchers actually differs between translation/rotation and pose/scaling. In Experiment 1, although the m-Metric shows users separated control between translation and rotation most of the time, an integrated isotonic control (OH) had better performance than separated isotonic control (OHS). In Experiment 2, the coupling of translation-scaling and rotation-scaling were less than the coupling of translation-rotation. The combination Scale+6DOF pose control disobeyed Jacob's perceptual/control structure matching theory (separable OHSS outperformed integral OHIS for a nominally perceptually integral task).

6.2 Limitations and Future Work

Further experiments are required to provide more substantial support for some of our inferences. For instance, we need another experiment to verify if decomposing translation and rotation in isotonic condition could perform similarly or better in bimanual mode providing integrate control compared with one-handed integral mode. Mendes et al. [23] performed a similar free-hand experiment including their 3DOF-hand condition which matches this idea. However, free-hand interactions lack the passive-haptic feedback of button balls, so possibly the outcomes could differ.

Besides, the OHS method of Chapter 5, Experiment 1, could be implemented differently. Instead of two modes, one for translation only and one for rotation only, 3 modes could be provided allows translation only, rotation only and rotation + translation. Under this condition, an interesting question is do users choose to only use rotation + translation mode? Or do they occasionally choose separated translation or separated rotation modes? Given their preferences and behavior how does this 3-mode version affect completion times compared to OH? However does it affect the m-Metric during periods where they choose to use rotation + translation mode?

Design and implement more manipulation techniques based on current results. For instance, although we discussed many advantages about using the mouse for the long duration tasks, due to its low DOF input property, more complicated movement mappings were required. In order to improve the intuitiveness of the interaction, we consider combining devices with higher DOF controls. Moreover, in the previous study, we found that trackball rotation got most positive feedback about intuitive control and long duration usage (Chapter 4 and [65]). Thus, one possible design is to keep the trackball for rotation control and resort other inputs for translation control.

Moreover, I hypothesize that input devices with more movement restrictions either in the form of resistance force (i.e. isometric control mode) or in the form of mechanically constrained DOFs (such as mouse confined to a desk surface), may benefit from some DOF separations. Zhai concluded that isotonic control is considered more natural and flexible than isometric control (such as the SpaceMouse) [11]. Although users could manipulate the SpaceMouse cap in 6DOFs, it's harder to control compared with isotonic input device and the cap can easily trigger unwanted integrated operations. And also hard for the users to control rotation and translation simultaneously. Thus, users tend to separate rotation/translation control even more for isometric Spaceball [16] seems to be for the purpose of simplifying the operations. For isotonic desktop input devices such as Globefish/GlobeMouse and my TM technique (Chapter 4), they have mechanically constrained DOFs from the desk surface or the devices' mechanical structure which do not allow users' hand to move freely in 3D for direct physical–to-virtual movement mapping, which is relatively complicated for the users to achieve wanted operations like the button ball. DOF separation strategy for devices with such restrictions could decompose the complicated operations to more than one operations but simpler for easier controls.

Thus, we infer that for operations that require 6DOF or lower DOF control with devices in isotonic position input which may be the prerequisite to apply the Jacob's principle [31], choose integral control if the control structure matches the perceptual structure of the visual task. When using input devices with significant restrictions from either force resistance or mechanical structure which do not allow isotonic control with direct movement mapping or with tasks having a more than 6DOF control requirement, choose separated DOF control to simplify manipulation process in order to achieve better performance.

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APPENDIX A: EXPERIMENT DOCUMENTS OBJECT MANIPULATION - I (FOR CHAPTER 3)

UNC CHARLOTTE

Research and Economic Development
Office of Research Compliance

9201 University City Blvd, Charlotte, NC 28223-0001
t/ 704.687.1876 f/ 704.687.0980 http://research.uncc.edu/compliance-ethics

Institutional Review Board (IRB) for Research with Human Subjects

Certificate of Approval

Protocol #	**13-06-29**		
Protocol Type:	**Expedited**	**7**	
Title:	**Evaluating Two-handed 3D Objects Docking in a Desktop VR for 3D Applications**		
Initial Approval:	**7/15/2013**		
Responsible Faculty	**Dr. Zachary**	**Wartell**	**Computer Science**
Investigator	**Mr. Jinbo**	**Feng**	**Computer Science**
Co-investigator	**Mr. Isaac**	**Cho**	**Computer Science**

After careful review, the protocol listed above was approved by the Institutional Review Board (IRB) for Research with Human Subjects under 45 CFR 46.111. This approval will expire one year from the date of this letter. In order to continue conducting research under this protocol after one year, the "Annual Protocol Renewal Form" must be submitted to the IRB. This form can be obtained from the Office of Research Compliance web page http://research.uncc.edu/compliance-ethics/human-subjects.

Please note that it is the investigator's responsibility to promptly inform the committee of any changes in the proposed research prior to implementing the changes, and of any adverse events or unanticipated risks to subjects or others.

Amendment and Event Reporting forms are available on our web page at: http://research.uncc.edu/compliance-ethics/human-subjects/amending-your-protocol.

M. Lyn Exum 7/18/13

Dr. M. Lyn Exum, IRB Chair Date

The UNIVERSITY of NORTH CAROLINA at CHARLOTTE
An Equal Opportunity/Affirmative Action Employer

Informed Consent for
Evaluating effectiveness of 3D object manipulation techniques in desktop VR for 3D applications

Project Purpose

This study examines four techniques for manipulating 3D objects in a computer generated, 3D virtual environment. The computer system uses a stereoscopic 3D display with head-tracking and a pair of 3D input devices. Participants will perform a series of 3D manipulation tasks using the four techniques which differ in whether they use one or two hands and differ in how physical manipulation of the 3D input devices controls the location, orientation and size of the manipulated 3D object.

Investigators

Jinbo Feng, Ph.D. Candidate, Computer Science
Isaac Cho, Ph.D. Computer Science
Zachary Wartell, Associate Professor, Computer Science

Eligibility

You may participate in this study if you are 18 years of age or higher and if you have 20/20 vision, corrected vision to 20/20 or higher (i.e. you can clearly read text on a computer workstation monitor), can comfortably use your arms, hands and fingers for everyday tasks and you can communicate in spoken English.

Overall Description of Participation

In the first step, we will demonstrate the computer system's stereoscopic display and head-tracking technology to make you familiar with them. Stereopsis is an important binocular depth cuegenerated by the differences between the two views of a scene seen from a person's two eyes. Head-tracking is a technology which tracks the position and orientation of participant's head to generate an optimal perspective image.We will demonstrate how to use a pair of 3D input devices called "button balls" that individually are like a 3D mouse. We will train you to use all these technologies by showing you how to view a 3D virtual environment and how to perform a navigation task (rotating, translating and scaling) using the button ball devices. Also, we will survey your experiences with 3D applications (e.g. 3D games and 3D movies) and your familiarity with using a computer and user interface.

Next, you will perform a series of box docking tasks. The docking task requires you select three target boxes and manipulate them to match the location, orientation and size of a "docking" box shown in the center of the screen. You will perform the task using four different object manipulation techniques which we will demonstrate to you. Briefly these four techniques are: a one-handed technique; a two-handed technique with a separated pitch operation; a two-handed technique with a separated one-handed rotation; a two-handed technique with a separated one-handed scale.

After you finish the experiment, you will take a post-experiment questionnaire.

Length of Participation

Participation should take approximately 30-50 minutes.

Risks and Benefits of Participation

While using virtual environment systems, some people experience slight symptoms of disorientation, nausea, or dizziness. These can be similar to "motion sickness" or the feeling experienced in wide-screen movies and theme park rides. We do not expect these to be strong or to last after participants leave the laboratory. if you feel uncomfortable and wish to stop the experiment, you are free to do so at any time without penalty by simply announcing your desire to stop.

The primary scientific benefit of the study is to compare and determine the effectiveness of one-handed object manipulation with two-handed object manipulation techniques for 3D applications in a desktop virtual reality system.

Volunteer Statement

You are a volunteer. The decision to participate in this study is completely up to you. If you decide to participate in the study, you may stop at any time. You will not be treated any differently if you decide not to participate in the study or if you stop once you have started.You can request to withdraw your segment after the testing is complete.

Confidentiality Statement

Any information about your participation, including your identity, is completely confidential. The following efforts will be taken to protect confidentiality and privacy:

1) The informed consent form will be kept in a locked filing cabinet, separate from the rest of the data.
2) All participants will be assigned a random ID consisting two randomly-generated initials (initials will not correspont to participants' name). The participants will only be referred by assigned alphanumeric codes both in internal communication between researchers or in the form of written reports.
3) The investigator and co-investigators will ask the participants not to mention their name or identify themselves during the recordings. The recording is only for internal use such as transcription and will not be made available to the public. Screenshots from the video recording might be published without disclosing the identify of any participants.
4) All digitally recorded files during the study will be kept in the Charlotte Visualization Center (room 437 in Woodward Hall) on password-protected computers. The files will be destroyed after two years by investigators under the guidance of the responsible faculty.

Statement of Fair Treatment and Respect

UNC Charlotte wants to make sure that you are treated in a fair and respectful manner. Contact the university's Research Compliance Office (704-687-1871) if you have questions about how you are treated as a study participant.

Approval Date

Participant Consent

I have read the information in this consent form. I have had the chance to ask questions about this study, and those questions have been answered to my satisfaction. I am at least 18 years of age, and I agree to participate in this research project. I understand that I will receive a copy of this form after it has been signed by me and the principal investigator of this research study.

______________________________________ _______________________
Participant Name (PRINT) DATE

____
Participant Signature

______________________________________ _______________________
Investigator Signature DATE

Pre-Questionnaires:

1. Your given ID number (Instructor only):

2. Your age:

3. Your gender:

4. Occupational Status: Undergraduate student ___

   Master Student ___

   PhD Student___

   Research Assistant/Fellow ___

   Staff-systems, technical ___

   Faculty ___

   Administrative Staff ___

   Other: ___________________

5. Your major is:

6. Are you colorblind? : Yes / No

7. Do you have any problems viewing the computer screen without it blurring if you sit 30 inches from the screen? Yes / No

8. Do you have any disabilities or injuries that might limit your ability to use either of your left or right arm, hand and/or fingers in everyday tasks such as writing, painting, using a computer mouse or advanced game controller? Yes/ No

9. Are you familiar with using a mouse and keyboard? Yes / No

10. Have you ever felt motion sick (dizziness or nausea) while playing a computer game or viewing a large, screen movie before? Yes / No

1. How often do you use a computer in your daily activities?

(Never) (A Great Deal)

1 2 3 4 5 6 7

2. How often do you play 2D computer games?

(Never) (A Great Deal)

1 2 3 4 5 6 7

3. How often do you play 3D computer games?

(Never) (A Great Deal)

1 2 3 4 5 6 7

4. How often do you play computer games(of any kind) on a computer/PC?

(Never) (A Great Deal)

1 2 3 4 5 6 7

5. How often do you play computer games using a game console, such as Nintendo®, XBox®, Sony Playstation®, other?

(Never) (A Great Deal)

1 2 3 4 5 6 7

6. How often do you play computer games using a game console with a motion capture device, such as XBox Kinect®, Sony Playstation Move®, or others?

(Never) (A Great Deal)

1 2 3 4 5 6 7

Definition: Stereoscopic 3D

Stereoscopic 3D refers to a display that creates a true 3D image that appears to pop-out in front of and behind the screen. These displays are found in some movie theaters, television sets and computer monitors. Most stereoscopic 3D display technologies known to consumers require they wear special glasses.

7. How often do you watch stereoscopic 3D movies in the theater?

(Never)						(A Great Deal)
1	2	3	4	5	6	7

8. How often do you play computer games or watch movies on an in-home television using stereoscopic 3D?

(Never)						(A Great Deal)
1	2	3	4	5	6	7

Definition: 3D User Interface

A "3D user interface" is a human-computer interface where the user views 3D computer graphics and interacts with those graphics by traveling through the 3D environment, and/or manipulating and changing the 3d environment. 3D user interfaces may or may not use stereoscopic 3D displays. Also 3D user interfaces may or may not use advanced 3D input devices such as the Microsoft Kinect, PlayStation Move, Nintendo Wii, etc.

If you have used any 3D user interfaces before, then describe what 3D user interfaces you have used and mention what type of display and input device technology you used with them.

____

____

____

Post-Questionnaires:

Manipulation techniques:

One-Handed technique – OH

Two-Handed technique with pitch -- TH

One-Handed technique with a separate scaling -- OTS

1. Overall, which object manipulation technique (OH, TH or OTS) was better than the others for the box selection task? Why?

2. Which box manipulation technique was best for rotating? Why?

3. Which box manipulation technique was best for box translation? Why?

4. Which box manipulation technique was best for box scaling? Why?

5. Overall, which box manipulation technique was more intuitive (i.e. felt more natural) to perform the task? Which one do you like best? Why?

6.

A) Did the target box size affect the task difficulty?

(Not At All) (Very Different)

1 2 3 4 5 6 7

B) Which one of the target box sizes made the task the easiest, harder or hardest?

7. How much arm fatigue did you feel with One-Handed technique?

(Not At All) (Very Painful)

1 2 3 4 5 6 7

8. How much arm fatigue did you feel with the Two-Handed technique with pitch?

(Not At All) (Very Painful)

1 2 3 4 5 6 7

9. How much arm fatigue did you feel with the One-Handed technique with a separate scaling?

(Not At All) (Very Painful)

1 2 3 4 5 6 7

Some people experience difficulty in perceiving a clear 3D stereoscopic image on the display. Often if the 3D image extends too far in front or behind the display surface, a person may perceive only two separate double images rather than a single 3D image. In some circumstances, a person may experience eye strain, visual fatigue or headaches when viewing this type of display system. Collectively, these negatives experiences are called “stereoscopic fusion problems”.

10. How frequently did you feel stereoscopic fusion problem during the object manipulations?

(Not At All)						(Very Often)
1	2	3	4	5	6	7

11. If you have any comments for this study, please give us feedback below:

APPENDIX B: EXPERIMENT DOCUMENTS OBJECT MANIPULATION - II (FOR CAPTHER 4)

UNC CHARLOTTE

Research and Economic Development
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Institutional Review Board (IRB) for Research with Human Subjects
Approval of Exemption

Protocol #	**15-02-13**			
Title:	**Comparing Four Object Manipulation Techniques in a Desktop 3D Environment**			
Date:	**2/9/2015**			
Responsible Faculty	**Dr.**	**Zachary**	**Wartell**	**Computer Science**
Investigator	**Mr.**	**Jinbo**	**Feng**	**Computer Science**
Co-investigator	**Dr.**	**Isaac**	**Cho**	**Computer Science**

The Institutional Review Board (IRB) certifies that the protocol listed above is exempt under category 2 (45 CFR 46.101).

Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, unless:

a) information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and

b) any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

This approval will expire one year from the date of this letter. In order to continue conducting research under this protocol after one year, the "Annual Protocol Renewal Form" must be submitted to the IRB. Please note that it is the investigator's responsibility to promptly inform the committee of any changes in the proposed research, as well as any unanticipated problems that may arise involving risks to subjects. Amendment and Event Reporting forms are available on our web site: http://research.uncc.edu/compliance-ethics/human-subjects/amending-your-protocol or http://research.uncc.edu/compliance-ethics/human-subjects/reporting-adverse-events

M.Ex 2/16/15

Dr. M. Lyn Exum, IRB Chair Date

UNCCHARLOTTE
The University of North Carolina at Charlotte

Informed Consent for
Comparing Four Object Manipulation Techniques in a Desktop 3D Experiment

Project Purpose

This study examines four techniques for manipulating 3D objects in a computer generated, 3D virtual environment. The computer system uses a desktop with standard mouse, keyboard, trackball and 3Dconnexion SpaceNavigator. Participants will perform a series of 3D manipulation tasks using the three techniques which differ in input devices and differ in how physical manipulation of the input devices controls the location, orientation and size of the manipulated 3D object.

Investigators

Jinbo Feng, Ph.D. candidate, Computer Science
Zachary Wartell, Associate Professor, Computer Science
Isaac Cho, Ph.D. Computer Science

Eligibility

You may participate in this study if you are 18 years of age or higher and if you have 20/20 vision, corrected vision to 20/20 or higher (i.e. you can clearly read text on a computer workstation monitor), can comfortably use your arms, hands and fingers for everyday tasks and you can communicate in spoken English.

Overall Description of Participation

In the first step, you will take a paper based Mental Rotation Test to determine your spatial ability.

Then, we will demonstrate and train you to use three different object manipulation techniques to perform object manipulation task (rotating, translating).

Next, you will perform a series of box docking tasks. The docking task requires you select three target boxes and manipulate them to match the location, orientation of a "docking" box shown in the center of the screen. You will perform the task using the two different object manipulation techniques.

After you finish all three manipulation techniques in the experiment, you will take a post-experiment questionnaire.

Length of Participation

Participation should take approximately 90 minutes for the experiment of Mental Rotation Test, the first two manipulation techniques.

Risks and Benefits of Participation

While using virtual environment systems, some people experience slight symptoms of disorientation, nausea, or dizziness. These can be similar to "motion sickness" or the feeling experienced in wide-screen movies and theme park rides. We do not expect these to be strong or to last after participants leave the laboratory. if you feel uncomfortable and wish to stop the experiment, you are free to do so at any time without penalty by simply announcing your desire to stop.

The primary scientific benefit of the study is to compare and determine the effectiveness and comfort among the Trackball + Mouse manipulation technique, Keyboard + Mouse manipulation technique and 3Dconnexion SpaceNavigator + Mouse manipulation technique for 3D applications in a desktop 3D system.

Volunteer Statement

You are a volunteer. The decision to participate in this study is completely up to you. If you decide to participate in the study, you may stop at any time. You will not be treated any differently if you decide not to participate in the study or if you stop once you have started. You can request to withdraw your segment after the testing is complete.

Confidentiality Statement

Any information about your participation, including your identity, is completely confidential. The following efforts will be taken to protect confidentiality and privacy:

1) The informed consent form will be kept in a locked filing cabinet, separate from the rest of the data.
2) All participants will be assigned a random ID consisting two randomly-generated initials (initials will not correspont to participants' name). The participants will only be referred by assigned alphanumeric codes both in internal communication between researchers or in the form of written reports.
3) The investigator and co-investigators will ask the participants not to mention their name or identify themselves during the recordings. The recording is only for internal use such as transcription and will not be made available to the public. Screenshots from the video recording might be published without disclosing the identify of any participants.
4) All digitally recorded files during the study will be kept in the Charlotte Visualization Center (room 437 in Woodward Hall) on password-protected computers. The files will be destroyed after two years by investigators under the guidance of the responsible faculty.

Statement of Fair Treatment and Respect

UNC Charlotte wants to make sure that you are treated in a fair and respectful manner. Contact the university's Research Compliance Office (704-687-1871) if you have questions about how you are treated as a study participant.

Approval Date

2/20/2015

Participant Consent

I have read the information in this consent form. I have had the chance to ask questions about this study, and those questions have been answered to my satisfaction. I am at least 18 years of age, and I agree to participate in this research project. I understand that I will receive a copy of this form after it has been signed by me and the principal investigator of this research study.

____________________________________ ______________________
Participant Name (PRINT) DATE

____
Participant Signature

____________________________________ ______________________
Investigator Signature DATE

Pre-Questionnaires:

1. Your given ID number (Instructor only):

2. Your age:

3. Your gender:

4. Occupational Status: Undergraduate student ___

    Master Student ___

    PhD Student___

    Research Assistant/Fellow ___

    Staff-systems, technical ___

    Faculty ___

    Administrative Staff ___

    Other: ___________________

5. Your major is:

6. Are you colorblind? : Yes / No

7. Do you have any disabilities or injuries that might limit your ability to use either of your left or right arm, hand and/or fingers in everyday tasks such as writing, painting, using a computer mouse or advanced game controller?   Yes/ No

8. Do you have any disabilities or injuries that might limit your ability to use either your left or right arm, hand and/or fingers in everyday tasks such as writing, painting, using a computer mouse or advanced game controller?   Yes/ No

9. Are you familiar with using a mouse and keyboard? Yes / No

10. Have you ever felt motion sick (dizziness or nausea) while playing a computer game or viewing a large, screen movie before? Yes / No

1. How often do you use a computer in your daily activities?

(Never)						(A Great Deal)
1	2	3	4	5	6	7

2. How often do you play 2D computer games?

(Never)						(A Great Deal)
1	2	3	4	5	6	7

3. How often do you play 3D computer games?

(Never)						(A Great Deal)
1	2	3	4	5	6	7

4. How often do you use 3D modeling software (Maya, Revit, Rhino, SketchUp, etc.)?

(Never)						(A Great Deal)
1	2	3	4	5	6	7

5. How often do you use trackball?

(Never)						(A Great Deal)
1	2	3	4	5	6	7

6. How often do you use 3Dconnexion SpaceNavigator?

(Never) (A Great Deal)

1 2 3 4 5 6 7

7. How often do you play computer games using a game console with a motion capture device, such as XBox Kinect®,Sony Playstation Move®, or others?

(Never) (A Great Deal)

1 2 3 4 5 6 7

Definition: 3D User Interface

A "3D user interface" is a human-computer interface where the user views 3D computer graphics and interacts with those graphics by traveling through the 3D environment, and/or manipulating and changing the 3d environment. 3D user interfaces may or may not use traditional input devices such as Keyboard, Mouse and Trackball and may or may not use advanced 3D input devices such as the Microsoft Kinect, PlayStation Move, Nintendo Wii, etc.

6. If you have used any 3D user interfaces before, then describe what 3D user interfaces you have used and mention what type of input device or technology you used with them.

Post-Questionnaires:

Manipulation Techniques:

1. Trackball + Mouse (TM) Technique

3. Keyboard + Mouse (KM) Technique

4. 3Dconnexion SpaceNavigator + Mouse (3M) Technique

1. Which box manipulation technique was better for rotating? Why?

2. Which box manipulation technique was better for box translation? Why?

3. Overall, which box manipulation technique was more intuitive (i.e. felt more natural) to perform the task?

4. Overall, which box manipulation technique do you like better? Why?

5. How much mental fatigue did you feel with the Trackball-Mouse technique?

(Not At All) (Moderately Fatiguing) (Extremely Fatiguing)

1 2 3 4 5 6 7

6. How much mental fatigue did you feel with the Keyboard-Mouse technique?

(Not At All) (Moderately Fatiguing) (Extremely Fatiguing)

1 2 3 4 5 6 7

7. How much mental fatigue did you feel with the 3Dconnexion SpaceNavigator + Mouse technique?

(Not At All) (Moderately Fatiguing) (Extremely Fatiguing)

1 2 3 4 5 6 7

8. How much physical fatigue did you feel with the Trackball-Mouse technique?

(Not At All) (Moderately Fatiguing) (Extremely Fatiguing)

1 2 3 4 5 6 7

9. How much physical fatigue did you feel with the Keyboard-Mouse technique?

(Not At All) (Moderately Fatiguing) (Extremely Fatiguing)

1 2 3 4 5 6 7

10. How much physical fatigue did you feel with the SpaceNavigator + Mouse technique?

(Not At All) (Moderately Fatiguing) (Extremely Fatiguing)

1 2 3 4 5 6 7

11. If you have used 3d modeling software before, what is your opinion on the two-handed Trackball-Mouse input method?

____

____

____

12. If you have any comments for this study, please give us feedback below:

____

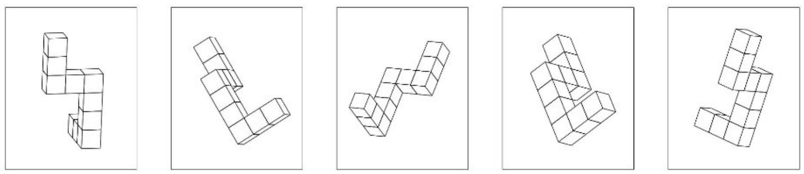
____

____

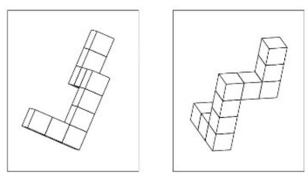
APPENDIX C: MENTAL ROTATION TEST
(FOR CAPTHER 4)

This test is composed of the figures provided by Shepard and Metzler (1978), and is, essentially, an Autocad-redrawn version of the Vandenberg & Kuse MRT test.

Please look at these five figures



Note that these are all pictures of the same object which is shown from different angles. Try to imagine moving the object (or yourself with respect to the object), as you look from one drawing to the next.

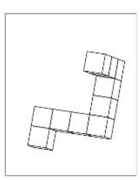


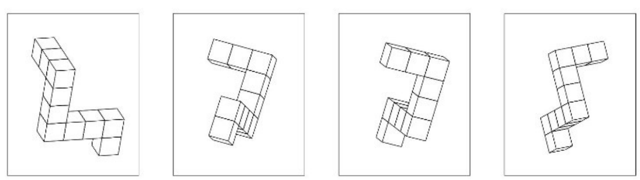
Here are two drawings of a new figure that is different from the one shown in the first 5 drawings. Satisfy yourself that these two drawings show an object that is different and cannot be "rotated" to be identical with the object shown in the first five drawings.

Now look at this object:

Two of these four drawings show the same object. Can you find those two? Put a big X across them.

1.

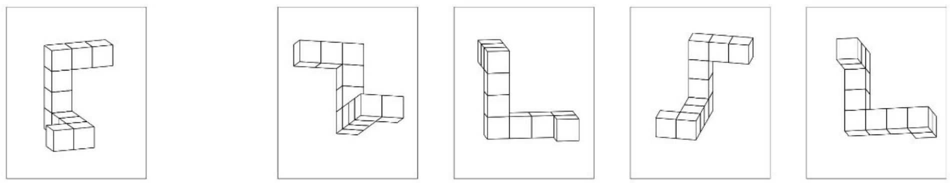




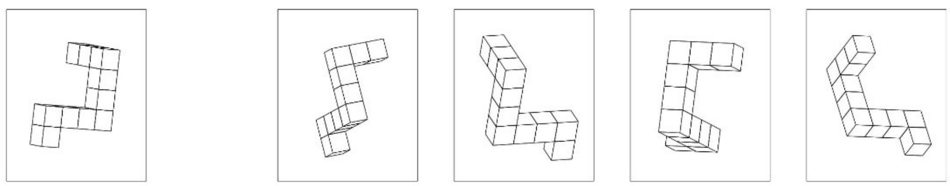
If you marked the first and third drawings, you made the correct choice.

Here are three more problems. Again, the target object is shown twice in each set of four alternatives from which you choose the correct ones.

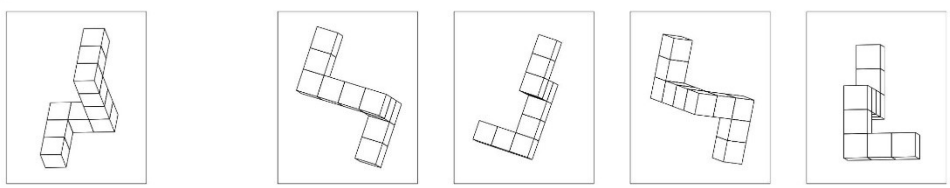
2.a



3.a



4.a

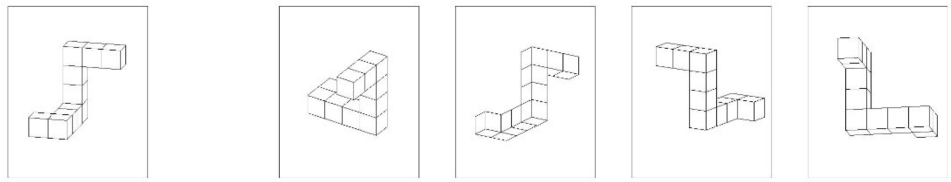


Correct Choice: 2: second and third
3: first and fourth
4: first and third

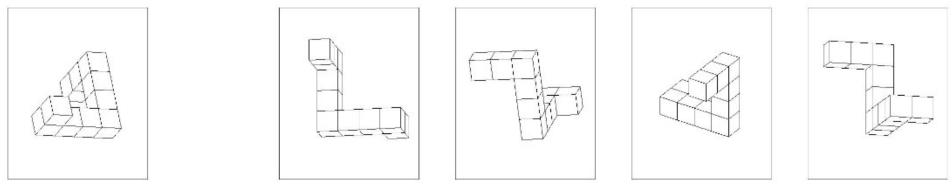
When you do the test, please remember that for each problem set there are two and only two figures that match the target figure.

You will only be given a point if you mark off both correct matching figures, marking off only one of these will result in no marks.

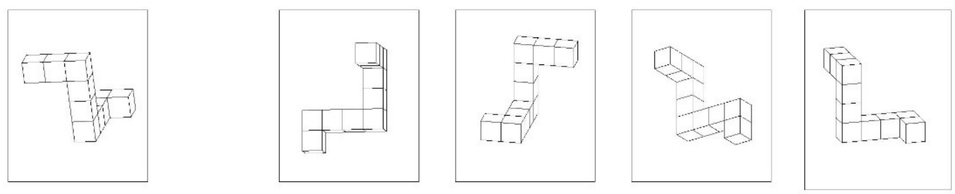
1.a



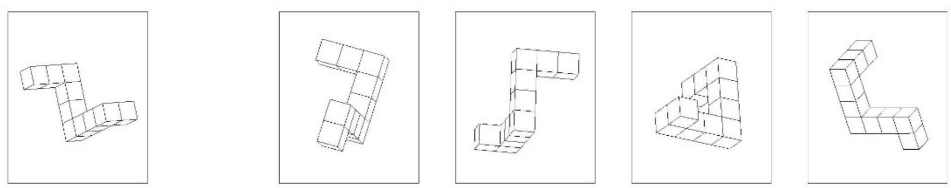
2.a



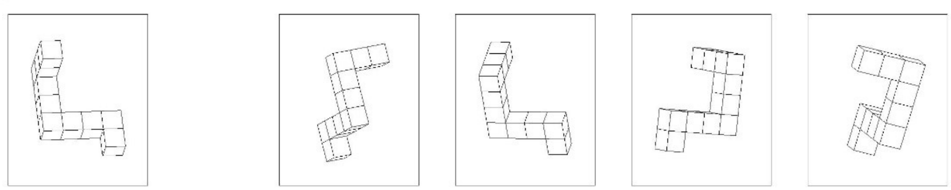
3.a



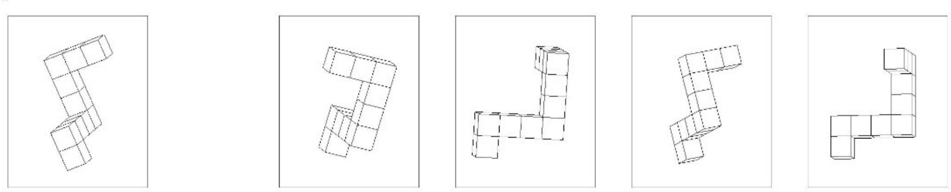
4.a



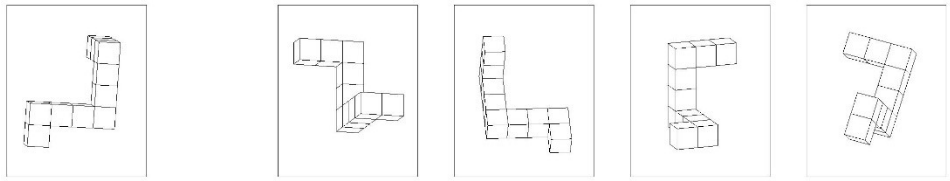
5.a



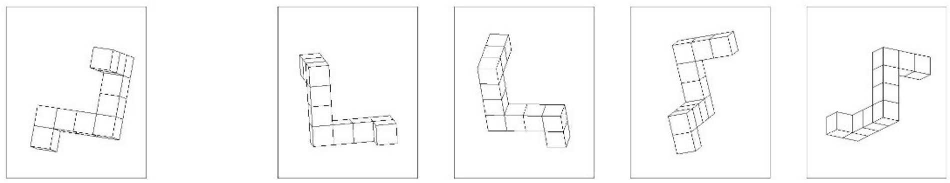
6.a



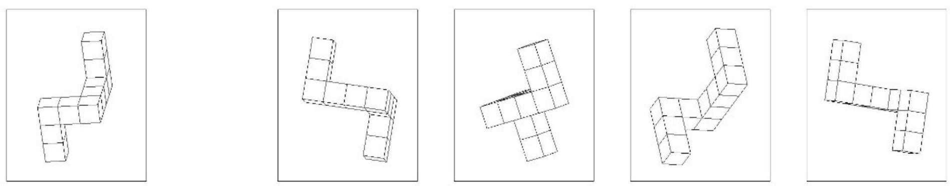
7.a



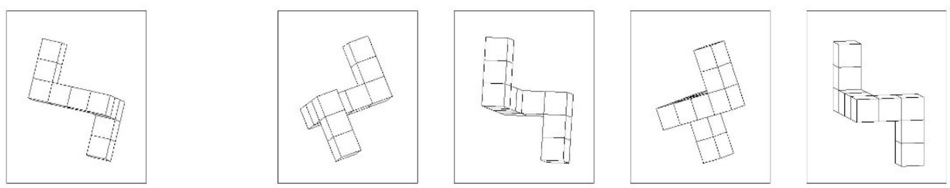
8.a



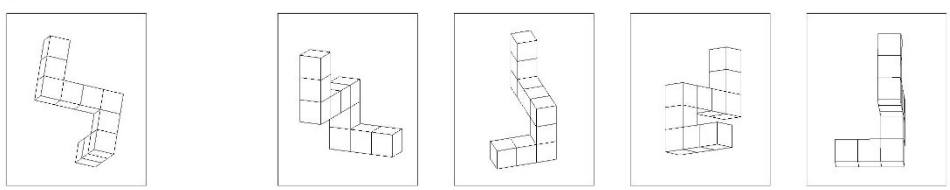
9.a



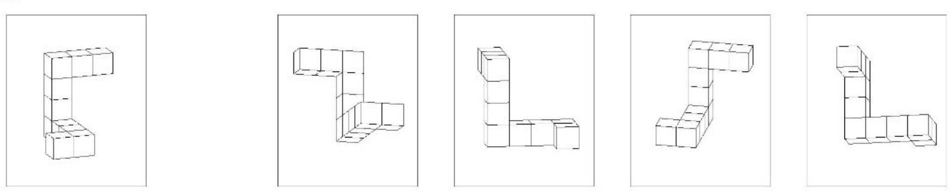
10.a



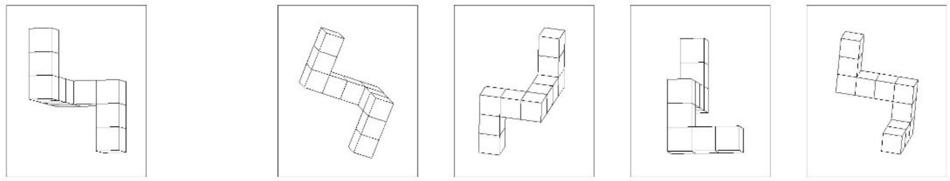
11.a



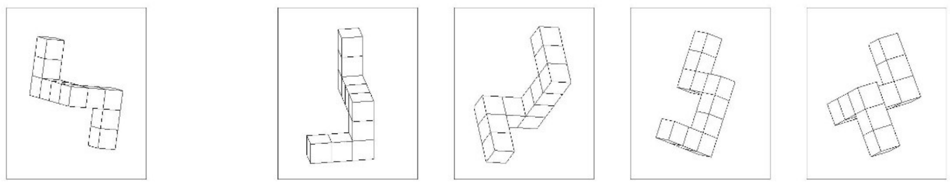
12.a



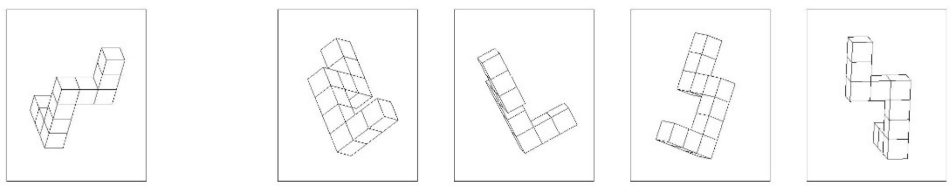
13.a



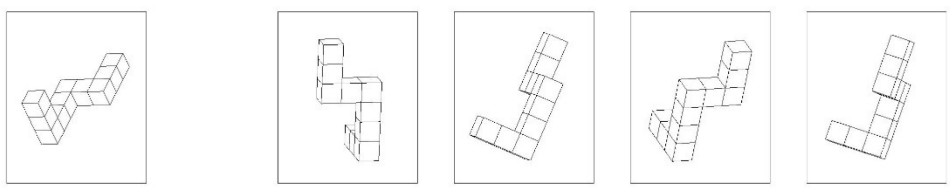
14.a



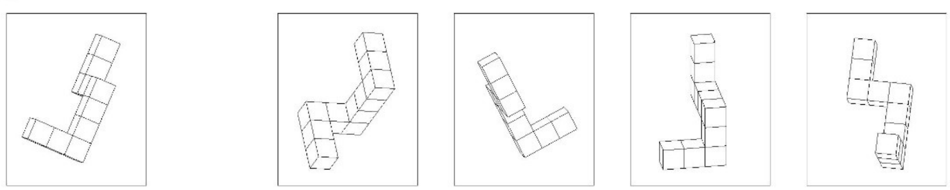
15.a



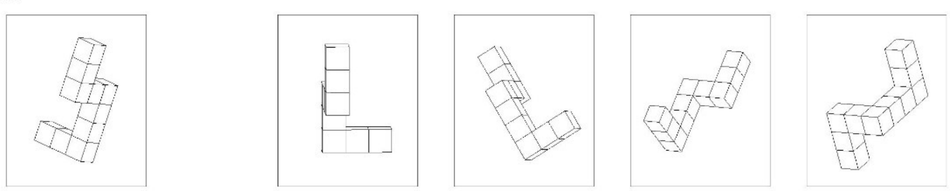
16.a



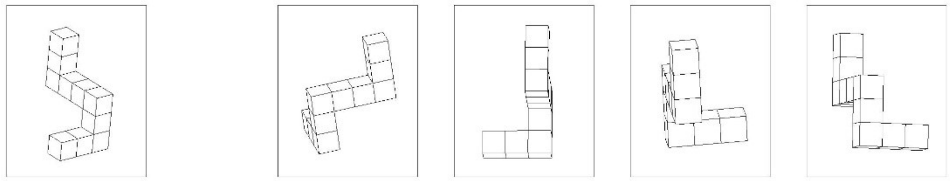
17.a



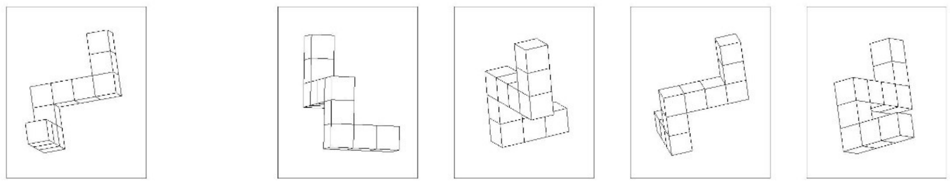
18.a



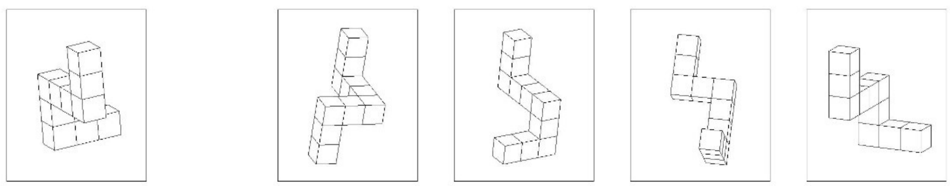
19.a



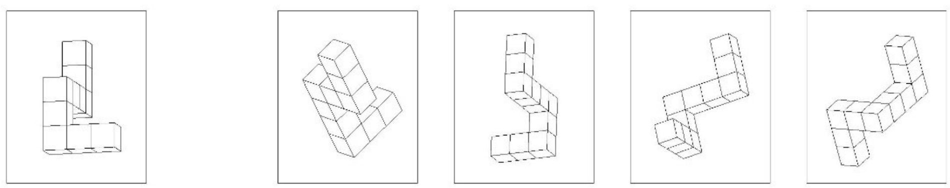
20.a



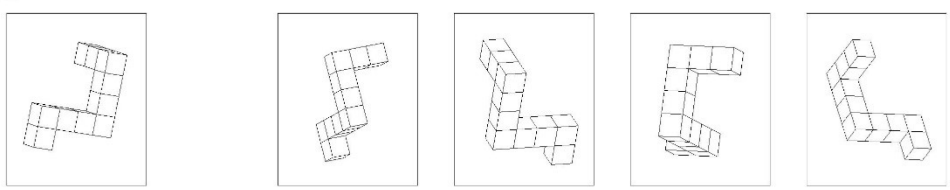
21.a



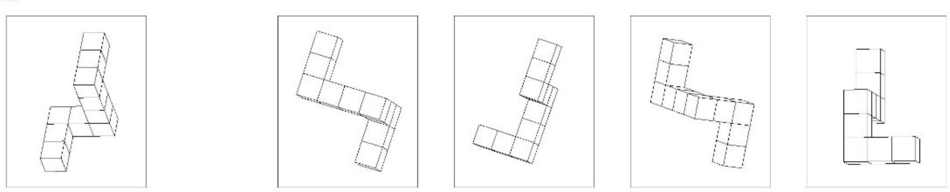
22.a



23.a



24.a



APPENDIX D: EXPERIMENT DOCUMENTS OBJECT MANIPULATION - III (FOR CAPTHER 5)

UNC CHARLOTTE

Research and Economic Development
Office of Research Compliance
9201 University City Blvd, Charlotte, NC 28223-0001
t/ 704.687.1876 f/ 704.687.0980 http://research.uncc.edu/compliance-ethics

Institutional Review Board (IRB) for Research with Human Subjects

Certificate of Approval

Protocol #	**15-08-27**		
Protocol Type:	**Expedited**	7	
Title:	**The Role of Integral Control in a 6 Degree of Freedom Docking Experiment**		
Initial Approval:	**9/14/2015**		
Responsible Faculty	**Dr. Zachary**	**Wartell**	**Computer Science**
Investigator	**Mr. Jinbo**	**Feng**	**Computer Science**
Co-investigator	**Dr. Isaac**	**Cho**	**Computer Science**

After careful review, the protocol listed above was approved by the Institutional Review Board (IRB) for Research with Human Subjects under 45 CFR 46.111. This approval will expire one year from the date of this letter. In order to continue conducting research under this protocol after one year, the "Annual Protocol Renewal Form" must be submitted to the IRB. This form can be obtained from the Office of Research Compliance web page http://research.uncc.edu/compliance-ethics/human-subjects.

Please note that it is the investigator's responsibility to promptly inform the committee of any changes in the proposed research prior to implementing the changes, and of any adverse events or unanticipated risks to subjects or others.

Amendment and Event Reporting forms are available on our web page at: http://research.uncc.edu/compliance-ethics/human-subjects/amending-your-protocol.

M. LE 9-18-15

Dr. M. Lyn Exum, IRB Chair Date

The UNIVERSITY *of* NORTH CAROLINA *at* CHARLOTTE

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UNC CHARLOTTE
College of Computing and Informatics

Informed Consent for
The Role of Integral Control in a 6Degree of Freedom Docking Experiment
Project Purpose

This is the first part of a study that includes an experiment in a computer generated, 3D virtual environment, to explore the role of degree-of-freedom (DOF) separation and integration between translation and rotation in different phases of an object alignment task. The computer system uses a stereoscopic 3D display with head-tracking and a pair of 3D input devices. Participants will perform a series of 3D tasks using two user interface techniques which differ in whether they allow integral or separate control of translation and rotation of the manipulated 3D object when manipulating the 3D input devices. This is a two part study. You will perform a series of similar 3D task but with a third different technique in the second part of this study which will take place one (1) week later.

Investigators

Jinbo Feng, Ph.D. Candidate, Computer Science
Isaac Cho, Ph.D. Computer Science
Zachary Wartell, Associate Professor, Computer Science

Eligibility

You may participate in this study if you are 18 years of age or older, have 20/20 vision, corrected vision to 20/20 or higher (i.e. you can clearly read text on a computer workstation monitor), can comfortably use your arms, hands and fingers for everyday tasks, and you can communicate in spoken English.

Overall Description of Participation

In the first step, we will demonstrate the computer system's stereoscopic display and head-tracking technology to make you familiar with them. Stereopsis is an important binocular depth cue generated by the differences between the two views of a scene seen from a person's two eyes. Head-tracking is a technology which tracks the position and orientation of a person's head to generate an optimal perspective image.

We will demonstrate how to use a pair of 3D input devices called "button balls" that individually is like a 3D mouse. We will train you to use all of these technologies by showing you how to view a 3D virtual environment and how to perform a manipulation task (rotating, translating and or scaling) using the button ball devices. Also, we will ask to complete a survey to tell us about your experiences with 3D applications (e.g. 3D games and 3D movies) and your familiarity with using a computer and user interface.

Next, you will perform a series of box docking tasks. The docking tasks require that you select a target box and manipulate it to match the location and orientation of a "docking" box shown in the center of the screen. You will perform the task using two different object manipulation techniques in the experiment. Briefly these two techniques are: a one-handed technique; and, a one-handed technique with separated translation and rotation.

Finally, you will be asked to come back one week later for a second visit to try a 3rd technique with similar tasks.

Length of Participation

Participation should take approximately 60 minutes for the first visit and about 30 minutes for the second visit.

Risks and Benefits of Participation

While using virtual reality systems, some people experience slight symptoms of disorientation, nausea, or dizziness. These can be similar to "motion sickness" or the feeling experienced in wide-screen movies and theme park rides. We do not expect these to be strong or to last after participants leave the laboratory. If you feel uncomfortable and wish to stop the experiment, you are free to do so at any time without penalty by simply announcing your desire to stop.

The primary scientific benefit of the study is to evaluate if the integral and separate control of translation and rotation affect object manipulation in different matching phases during 3D docking task.

Volunteer Statement

You are a volunteer. The decision to participate in this study is completely up to you. If you decide to participate in the study, you may stop at any time. You will not be treated any differently if you decide not to participate in the study or if you stop once you have started. You can request to withdraw your segment after the testing is complete.

Confidentiality Statement

Any information about your participation, including your identity, is confidential to the extent possible. The following efforts will be taken to protect confidentiality and privacy:
1) The informed consent form will be kept in a locked filing cabinet, separate from the rest of the data.
2) All participants will be assigned a random ID consisting two randomly-generated initials (initials will not correspont to participants' name). The participants will only be referred by assigned alphanumeric codes both in internal communication between researchers or in the form of written reports.
3) The investigator and co-investigators will ask the participants not to mention their name or identify themselves during the recordings. The recording is only for internal use such as transcription and will not be made available to the public. Screenshots from the video recording might be published without disclosing the identify of any participants.
4) All digitally recorded files during the study will be kept in the Charlotte Visualization Center (room 437 in Woodward Hall) on password-protected computers. The files will be destroyed after two years by investigators under the guidance of the responsible faculty.

Statement of Fair Treatment and Respect

UNC Charlotte wants to make sure that you are treated in a fair and respectful manner. Contact the university's Research Compliance Office (704-687-1871) if you have questions about how you are treated as a study participant.

Approval Date

This form was approved for use on *September 14, 2015* for a period of one (1) year.

Participant Consent

I have read the information in this consent form. I have had the chance to ask questions about this study, and those questions have been answered to my satisfaction. I am at least 18 years of age, and I agree to participate in this research project. I understand that I will receive a copy of this form after it has been signed by me and the principal investigator of this research study.

______________________________________ _______________________
Participant Name (PRINT) DATE

____
Participant Signature

______________________________________ _______________________
Investigator Signature DATE

Pre-Questionnaires:

1. Your given ID number (Instructor only):

2. Your age:

3. Your gender:

4. Occupational Status: Undergraduate student ___

   Master Student ___

   PhD Student___

   Research Assistant/Fellow ___

   Staff-systems, technical ___

   Faculty ___

   Administrative Staff ___

   Other: ___________________

5. Your major is:

6. Are you colorblind? : Yes / No

7. Do you have any problems viewing the computer screen without it blurring if you sit 30 inches from the screen? Yes / No

8. Do you have any disabilities or injuries that might limit your ability to use either of your left or right arm, hand and/or fingers in everyday tasks such as writing, painting, using a computer mouse or advanced game controller? Yes/ No

9. Are you familiar with using a mouse and keyboard? Yes / No

10. Have you ever felt motion sick (dizziness or nausea) while playing a computer game or viewing a large, screen movie before? Yes / No

1. How often do you use a computer in your daily activities?

(Never)						(A Great Deal)
1	2	3	4	5	6	7

2. How often do you play 2D computer games?

(Never)						(A Great Deal)
1	2	3	4	5	6	7

3. How often do you play 3D computer games?

(Never)						(A Great Deal)
1	2	3	4	5	6	7

4. How often do you play computer games (of any kind) on a computer/PC?

(Never)						(A Great Deal)
1	2	3	4	5	6	7

5. How often do you play computer games using a game console, such as Nintendo®, XBox®, Sony Playstation®, other?

(Never)						(A Great Deal)
1	2	3	4	5	6	7

6. How often do you play computer games using a game console with a motion capture device, such as XBox Kinect®, Sony Playstation Move®, or others?

(Never) (A Great Deal)

1 2 3 4 5 6 7

Definition: Stereoscopic 3D

Stereoscopic 3D refers to a display that creates a true 3D image that appears to pop-out in front of and behind the screen. These displays are found in some movie theaters, television sets and computer monitors. Most stereoscopic 3D display technologies known to consumers require they wear special glasses.

7. How often do you watch stereoscopic 3D movies in the theater?

(Never)						(A Great Deal)
1	2	3	4	5	6	7

8. How often do you play computer games or watch movies on an in-home television using stereoscopic 3D?

(Never)						(A Great Deal)
1	2	3	4	5	6	7

Definition: 3D User Interface

A "3D user interface" is a human-computer interface where the user views 3D computer graphics and interacts with those graphics by traveling through the 3D environment, and/or manipulating and changing the 3d environment. 3D user interfaces may or may not use stereoscopic 3D displays. Also 3D user interfaces may or may not use advanced 3D input devices such as the Microsoft Kinect, PlayStation Move, Nintendo Wii, etc.

9. If you have used any 3D user interfaces before, then describe what 3D user interfaces you have used and mention what type of display and input device technology you used with them.

____
____
____

Post-Questionnaires 1:

Manipulation techniques:

One-Handed technique – one button ball controls pose	(OH)
One-Handed technique with separate translation and rotation	(OHS)
One-Handed technique with separate and integral control	(OHSI)

1. Which box manipulation technique was best for rotating? Why?

____
____
____
____

2. Which box manipulation technique was best for box translation? Why?

____
____
____
____

3. Overall, which box manipulation technique was more intuitive (i.e. felt more natural) to perform the task? Which one do you like best? Why?

____
____
____
____

4. How much arm fatigue did you feel with OH technique?

(Not At All) (Very Painful)

1 2 3 4 5 6 7

5. How much arm fatigue did you feel with OHS technique?

(Not At All) (Very Painful)

1 2 3 4 5 6 7

6. How much arm fatigue did you feel with OHSI technique?

(Not At All) (Very Painful)

1 2 3 4 5 6 7

Some people experience difficulty in perceiving a clear 3D stereoscopic image on the display. Often if the 3D image extends too far in front or behind the display surface, a person may perceive only two separate double images rather than a single 3D image. In some circumstances, a person may experience eye strain, visual fatigue or headaches when viewing this type of display system. Collectively, these negatives experiences are called “stereoscopic fusion problems”.

7. How frequently did you feel stereoscopic fusion problem during the object manipulations?

(Not At All) (Very Often)

1 2 3 4 5 6 7

8. If you have any comments for this study, please give us feedback below:

____

____

____

UNC CHARLOTTE
Research and Economic Development
Office of Research Compliance
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t/ 704.687.1876 f/ 704.687.0980 http://research.uncc.edu/compliance-ethics

Institutional Review Board (IRB) for Research with Human Subjects

University of North Carolina at Charlotte

Approval of Amendment

Protocol #	**15-08-27**
Title:	**The Role of Integral Control in a 6 Degree of Freedom Docking Experiment**
Date:	**10/13/2015**

Investigator	**Mr. Jinbo**	**Feng**	**Computer Science**
Responsible Faculty	**Dr. Zachary**	**Wartell**	**Computer Science**
Co-investigator	**Dr. Isaac**	**Cho**	**Computer Science**

The Institutional Review Board (IRB) has approved the amendment of the protocol listed above for Research with Human Subjects.

Please note that it is the investigator's responsibility to promptly inform the committee of any changes in the proposed research, as well as any unanticipated problems that may arise involving risks to subjects.

Amendment Details: The purpose of the study is to evaluate object manipulation in a 3D virtual environment. The study uses different object manipulation techniques to explore how participants interact with a virtual object and navigate the object (i.e. manipulate the object) in the 3D environment. The manipulation techniques use six (6) degrees-of-freedom (DOF) which include position (x, y, x), and orientation (yaw, pitch, roll). This amendment is intended to expand the study to include experiments to allow consideration of a seventh DOF (7DOF); the 7th DOF being scale. The study procedures for the new experiments will be the same as with the 6DOF experiments. Participants will complete a pre-experiment questionnaire (currently approved), followed by a demonstration of the virtual environment and associated equipment/devices. After the demonstration, participants will complete the object manipulation tasks and finally complete a post-experiment questionnaire (revised for the new experiments). The consent document is updated accordingly.

M. Ly Exum — 10/22/15

Dr. M. Lyn Exum, IRB Chair — Date

Post-Questionnaires 2:

Manipulation techniques:

One-Handed pose with separate scaling (OHSS)

One-Handed pose with integral scaling (OHIS)

One-Handed pose with separable scaling (OHSIS)

1. Which box manipulation technique was best for scaling control? Why?

____

____

____

____

2. Which box manipulation technique was best for 7DOF control as a whole? Why?

____

____

____

____

4. Overall, which box manipulation technique was more intuitive (i.e. felt more natural) to perform the task? Which one do you like best? Why?

____

____

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5. How much arm fatigue did you feel with OHSS technique?

(Not At All) (Very Painful)

1 2 3 4 5 6 7

6. How much arm fatigue did you feel with OHIS technique?

(Not At All) (Very Painful)

1 2 3 4 5 6 7

7. How much arm fatigue did you feel with OHSIS technique?

(Not At All) (Very Painful)

1 2 3 4 5 6 7

Some people experience difficulty in perceiving a clear 3D stereoscopic image on the display. Often if the 3D image extends too far in front or behind the display surface, a person may perceive only two separate double images rather than a single 3D image. In some circumstances, a person may experience eye strain, visual fatigue or headaches when viewing this type of display system. Collectively, these negatives experiences are called “stereoscopic fusion problems”.

9. How frequently did you feel stereoscopic fusion problem during the object manipulations?

(Not At All) (Very Often)

1 2 3 4 5 6 7

10. If you have any comments for this study, please give us feedback below:

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