2007

Assessment of haptics-based interaction for assembly tasks in virtual reality

Dao Minh Vo
Iowa State University

Assessment of haptics-based interaction for assembly tasks in virtual reality

by

Dao Minh Vo

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Mechanical Engineering

Program of Study Committee:
Judy M. Vance, Major Professor
James H. Oliver
Chris Harding
Mervyn G. Marasinghe

Iowa State University

Ames, Iowa

2007

UMI Number: 1443122

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

Upon completing my graduate coursework, I strongly believe that I have grown academically, professionally, and personally from the support of several important individuals. First, I would like to thank Dr. Judy Vance for providing me with valuable experiences while under her tutelage. I have enjoyed all aspects of working with her and respect her drive and motivation. She has shown an immense amount of patience during my development, and I am forever indebted. I would like to express gratitude to Dr. Jim Oliver, Dr. Chris Harding, and Dr. Mervyn Marasinghe for their willingness to participate on my committee and their insight concerning the research.

I would like to thank John Deere and Company for funding the graduate research. I am grateful for my family and friends for all of their love and support. They have provided me with the motivation to excel and work hard at everything in life. I am thankful to Abhishek Seth, Denis Dorozhkin, Hai-jun Su, Daniela Faas, and Brad Howard for their assistance and dedication. I have the utmost respect for each one and wish them the very best in their future endeavors. I appreciate the entire staff at the Virtual Reality Applications Center for providing a supportive environment.

ABSTRACT

This thesis examines the benefits of haptics-based interaction for performing assembly-related tasks in a virtual environment. A software application that combined freeware and open-source software development kits was developed and demonstrated principles of physics-based modeling in a haptics-enabled immersive virtual environment. A user study was designed to evaluate subjects in performing a series of experiments relevant to the assembly engineering process including weight recognition, part positioning, and assembly simulation. Each experiment featured a structure based on factorial combinations of effects, resulting in a series of designed trials. Methods of assessing user performance were established based on task completion time and accuracy. Using a randomized complete block design, a sample population of forty individuals performed all trials within the experiments in random sequences. Statistical methods were used to analyze the performances of individuals upon the conclusion of the study. When compared to visuals-only methods, the results show that haptics-based interaction is beneficial in improving performance including reduced completion times for weight comparisons, higher placement accuracy when positioning virtual objects, and steadier hand motions along three-dimensional trajectories. Furthermore, the results indicate that the accuracy in weight identification is dependent on both the hand controlling the object and sensory modality used. The study was inconclusive in determining the affect of haptics-based interaction on completion times when positioning objects or completing manual assembly tasks.

CHAPTER 1. INTRODUCTION

The concept of a computer-generated environment has existed for several decades. Ivan Sutherland, the father of computer graphics, envisioned:

> *The ultimate display would…be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining* (Sutherland 1965).

To mimic real-world interaction, a virtual environment (VE) requires four key elements: three-dimensional stereoscopic viewing, position tracking, multiple sensory stimuli, and object to object interaction (Jayaram et al. 2001).

Virtual reality (VR) technology has been applied to many engineering areas such as product design, maintenance and assembly planning. Gomes de Sa and Zachmann (1998) demonstrated the utility of VR for evaluating a prototype of an automobile design. Virtual assembly is the ability to assemble CAD models of parts using a three-dimensional immersive interface with natural human motion (Kim and Vance 2004). One example of a virtual assembly simulation is the Virtual Assembly Design Environment (VADE) developed at Washington State University (Jayaram et al. 1997). This system was capable of exchanging geometric data of part models and assembly constraints from Pro/Engineer to an immersive virtual environment.

As the use of VR expands, researchers continue to investigate methods for increasing the realism experienced within virtual simulations. These simulations rely on visualization as a primary method of conveying information. Research efforts have examined haptics-based interaction to convey additional sensory cues. The Haptic Integrated Dis/Re-Assembly

(HIDRA) simulation environment developed at Georgia Tech University (McDermott and Bras 1999) incorporated haptic feedback for user interaction. The system featured two haptic devices configured for object manipulation using a pinch-like gesture. Frohlich et al. (2000) developed a responsive workbench system for virtual assembly. Their system presented a set of haptics-enabled virtual tools that permitted the use of multiple hands. Each interaction tool included a maximum of four virtual springs that connected a user-controlled outer frame to an interior frame that cradled the manipulated object. System for Haptic Assembly and Realistic Prototyping (SHARP) developed at Iowa State University (Seth et al. 2005) presented a cross-platform solution for performing virtual assembly sequences within an immersive simulated environment. The application was capable of importing complex CAD geometry into the virtual environment and featured a dual-handed haptic device interface, stereoscopic viewing with head tracking, and network communication.

Although incorporating haptics within a virtual environment provides users with a method of interacting with virtual objects, it increases the complexity of virtual environments due to hardware and software requirements. Identifying the benefits of haptics on user performance presents a unique research challenge and is the focus of this research.

1.1 Objective and Motivation

The objective of this research is to assess the performance benefits of haptics-based interaction for virtual assembly. We will determine whether completion times and several measures of accuracy are affected by haptic feedback including and identify assembly tasks where haptic feedback affects user performance. To achieve this goal, user performances of the same assembly task with two different sensory feedbacks are compared: a visual-only feedback and a method with both visual and haptic cues. The methodologies for the current research feature three phases: development of a virtual assembly application, a user study investigation, and analysis of data collected in user study using statistical methods.

1.2 Organization of the Thesis

Chapter 2 discusses elements of virtual reality for achieving realistic simulations including collision detection, physics-based modeling, and haptics-based interaction. Chapter 3 presents the design of the user study including software application, framework, preliminary and final investigations, and methods of data analysis. Chapters 4, 5, and 6 introduce three assembly-related experiments including weight recognition, part positioning, and assembly simulation. The final chapter of the thesis summarizes the research contributions and outlines future work.

CHAPTER 2. REALISTIC SIMULATION IN VIRTUAL REALITY

2.1 Introduction

Virtual reality can provide several benefits to industry by reducing costs associated with the product development process. It has been approved a powerful tool and applied to engineering applications such as conceptual design, preliminary design and analysis, manufacturing planning, and factory layout (Jayaram et al. 2001).

There are several requirements for developing a realistic simulation for virtual assembly. The first is the ability to detect collisions between virtual objects. This provides the necessary information to identify contacting models. The second requirement is to simulate the physical behavior and interactions of virtual objects similar to their real world counterparts. The third requirement is that the simulation must present information in an intuitive manner through haptic feedback, position and head tracking, or stereoscopic viewing.

2.2 Collision Detection

The implementation of collision detection within the software program structure provides the first step in achieving a realistic virtual environment. There are two major methods for detecting collisions: polygon-based method and volume-based method (Kim and Vance 2004). Polygon-based collision detection method reports the result by checking if two triangles (polygon) overlap. Example libraries are SWIFT which requires that the data define a convex polyhedra that distinguishes internal and external regions of space and RAPID and V-Collide which do not require the geometry to be of bounded form (Lin and Gottschalk 1998). In both classifications, vertices and triangle indices provide the necessary information for constructing the collision representation. Since the geometric information is associated with both the collision and graphics representation, accuracy of collision detection is dependent on fineness of triangle mesh.

Volume-based collision detection method generates a set of volume elements of a customized size to approximate the geometry of the part model while additional volume elements represent the interior and exterior regions (McNeely et al. 1999). An example is Boeing's Voxmap Pointshell (VPS) software which has been extensively researched at Iowa State University (Kim and Vance 2003). The voxels (small cubic) assist in determining whether collisions have occurred, the locations of collision, and depth of penetration of the colliding parts. In VPS, the shape of a dynamic model is approximated by a network of voxel center points called "point shell" and a static model is approximated by a network of voxels called "voxmap". Collision detection occurs when the point shell of the dynamic model interferes with the voxmaps of the static objects. The accuracy of volume-based collision detection is dependent on the size of the voxels. The smaller the voxel size, the more accurate of the part geometry, but more processing time and memory requirements.

2.3 Physics-Based Modeling

After detecting collisions and identifying points of contact, the next step involves the rendering of physical responses. The goal of physics-based modeling is to simulate part interaction in the VE such that all objects and interactions within the virtual simulation react similarly to their real counterparts. Entities in everyday life adhere to the laws of physics including applied external forces, static and dynamic states, and exhibit physical properties such as mass, friction, and hardness. The key is to model these governing rules into the virtual environment. Physics-based modeling approach utilizes Newtonian equations to compute the motions of rigid bodies within a simulation.

Three well-regarded methods for simulating physical behaviors include impulse-based, constraint-based, and penalty-based. Mirtich and Canny (1995) developed an approach to simulating dynamics of rigid bodies known as the impulse-based method. This technique incorporates the continuous application of equal and opposite impulses between contacting models. After applying the impulse at the points of contact, updates for the position of the body's center of mass and angular velocity are applied. This approach is capable of handling a wide assortment of collision scenarios including rolling, sliding, and resting conditions at interactive simulation rates.

The constraint-based method was extensively researched by Baraff and Witkin (2001) and involved computing force quantities from conditions of constrained motion for impenetrable bodies. This technique simulates the motion of an object along a trajectory until it has interpenetrated with another object. The solver determines the last time interval in which the bodies' surfaces were in contact and updates their physical states. This method yielded accurate calculation of reaction forces at the expense of computing performance.

The penalty-based method for determining the dynamic state of objects after collision employs a spring and damper system (Erleben et al. 2005). The time-dependent Newtonian equation, 2.1, calculates the applied penalty force, F. This force quantity separates two bodies that have interpenetrated beyond a specified threshold.

$$m\ddot{x} + b\dot{x} + kx = F \tag{2.1}$$

The variable m indicates the mass of the body while b and k denote damping and spring coefficients, respectively. These values are user-defined within a simulation environment while the solver computes quantities such as acceleration, velocity, and displacement for the moving body.

2.4 Haptics-Based Interaction

Salisbury and Srinivasan (1997) define computer haptics as the discipline concerned with the techniques and processes associated with generating and displaying synthesized haptic stimuli to the human user. They note that haptic rates ranging from 500 to 2,000 Hz are required to render force feedback with minimal noise vibrations. This is due to the human hand's sensitivity in detecting tactile vibrations (250 Hz), and kinesthetic resolution for changes in finger position (1 mm), velocity (10%), and acceleration (20%) (Burdea 1996). Haptic cues include force and tactile feedback. Tactile feedback concerns sensory information resulting from skin contact with objects including geometry, smoothness, slippage, and temperature. Force feedback involves rendering properties including weight, inertia, resistance, and hardness of virtual objects. The current research of haptics-based interaction concerns only force rendering.

Within a simulation, haptic feedback provides users with an opportunity to interpret virtual objects with sensory modalities other than sight and sound. From an input standpoint, traditional computer systems utilizing a keyboard and two-dimensional mouse device are counterintuitive when interacting within a three-dimensional virtual environment. Massie (1998) proposed the value of haptic feedback in several contexts:

- Providing feedback to help position objects accurately in 3D space.
- Resolving visual ambiguities by letting users feel the models.
- Communicating physical properties of objects.

- Letting users naturally and continuously manipulate models.

2.4.1 Haptic Devices

According to the portability of the mechanisms, haptic devices are categorized as grounded haptic devices and portable haptic devices. Grounded haptic devices feature a frame of reference that is fixed to either a desktop, ceiling, or wall (Burdea 1996). The grounded nature of the device provides mechanical stability for the system and permits the rendering of large force quantities including the weight of virtual objects and resistance. However, it presents limitations in terms of restricting users' range of motion to the extents of the haptic workspace. Some of the commercially available grounded haptic devices include the PHANToM™ series (Sensable Technologies 2007), the Omega.x™ interface (Force Dimension 2001-2007), and the Virtuose™ family of devices (Haption 2007).

Portable haptic devices utilize user's body such as back, chest, arm, or palm as the base frame (Burdea 1996). Examples of portable haptic devices include the Rutgers Master I and II developed at Rutgers University, and Immersion's CyberGrasp™ (Immersion Corporation 2007). They usually provide users a larger range of free motion than the grounded haptic devices. However, wearing such equipment may affect the interpretation of simulated force feedback.

2.4.2 Issues

The workspace of a haptic device limits the effectiveness in simulating industrial assembly operations that demand a large range of motion (Hollerbach 2000). Research work conducted by Fischer and Vance (2003) addressed this issue by putting a PHANToM™ 1.5 device on a movable platform. An algorithm has been developed to define a virtual volume that mapped the haptic device's position within the simulation. It has been demonstrated its usage in a six-sided CAVE environment.

A second limitation of haptic devices concerns the force rendering capabilities. Common devices such as the PHANToM™ series only provide three degree of freedom point force rendering without torque feedback (Massie 1998). This limitation restricts the rendering of touch-based information resulting from surface to surface contact. In addition, the maximum force output capabilities also present a limit to the use of the haptic devices. For instance, the PHANToM™ Premium 1.5 High Force™ can exert a maximum force output of 37.5 N (8.4 lbf.); a quantity that is less than the weight of many real assembly components.

2.5 Previous Research

Identifying the utility of haptic-based interaction has motivated research efforts from several institutions. In these investigations, researchers have examined the influence of haptic feedback on users' ability to interpret force information or to assist in task completion. Studies concerning haptics that are relevant to virtual assembly include weight recognition, performing spatial tasks, and manual assembly.

2.5.1 Weight Recognition

Researchers from Washington State University (Gurocak et al. 2003) examined weight sensations using a prototype haptic device, the AirGlove. The study involved three treatments using multiple pairs of blocks with distinct weight differences. Subjects had to identify the lightest block using their right hand. The first treatment involved pairs of real cubes made from wood material. The second treatment featured pairs of cubes simulated in a virtual assembly design environment (Jayaram et al. 1997) that were manipulated using the AirGlove device. The third treatment in the study was similar to the second, but included prerecorded air jet sound to disguise auditory noise produced from the haptic interface. In all three treatments, performance was assessed based on correct identification of the lighter component and task completion time. After data collection and analysis, their study concluded that treatments involving real cubes produced the most desirable results in terms of accurate recognition of lightest component (100%) and time of completion and the two treatments using virtual cubes, resulted in 88% response accuracy. Each of the two treatments that involved virtual cubes required a greater amount of time than the treatment involving real cubes.

Coutee and Bras (2004) also investigated weight sensations in real and virtual environments. In three experiments, users compared the weight differences between pairs of cubes: two real, two virtual, and one from each domain. In all three cases, a control cube with a mass of 100 grams was compared with cubes of lesser and greater masses. In trials involving cubes within the same environment, participants used one hand to estimate the weight while the third procedure involved the use of both hands. For tests in the virtual environment, users interacted with the virtual objects using two PHANToM™ haptic devices configured for single-handed pinch gesture. The simulation of the virtual environment was performed using the HIDRA application (McDermott and Bras 1999). The researchers concluded that participants were able to distinguish the weight between two real cubes with a higher success rate and in faster time (70%, 12.10 seconds) than experiments involving virtual counterparts (51%, 18.12 seconds). They also concluded that the tolerance of differentiating weights between two real cubes was approximately 20 grams while the results from the virtual cube were inconclusive.

2.5.2 Spatial Tasks

Arsenault and Ware (2000) examined the relationship between hand-eye coordination and haptic feedback. The investigators were interested in the effects of head tracking and force rendering when completing a Fitts tapping task between two cylindrical targets. User performance was evaluated based on interval tap times and error in failing to contact targets. Three factors were used: with and without head tracking, haptics and non-haptics, and various target distances. In non-haptic trials, participants relied on visual cues to perceive contact between cursor and target, while the haptics trials included rendered contact forces. The investigators found that haptic interaction using the PHANToM™ device improved the user performance of the tapping task in terms of time (12% interval reduction) and error.

Volkov and Vance (2001) examined the effectiveness of force feedback to evaluate virtual prototypes. Their simulation presented users with a digital mockup of an automobile interior design. Participants used a haptic device to provide input into the simulation. In haptic and non-haptic treatments, subjects estimated the distances between the virtual components. Their work concluded that participants using force feedback were able to complete the evaluations in less time than subjects who used only visual perception. The researchers noted the use of haptic or non-haptic sensory methods did not influence to correctness of response from users.

Using a similar Fitts tapping task, O'Malley et al. (2006) examined the use of haptics-based interaction for performance enhancement and training. Their work presented a shared control force rendering method in which haptic cues guided hand motions along a two-dimensional trajectory. The research involved two studies to evaluate performance using shared control, virtual fixturing, and non-haptics assistance methods. The first study examined subjects in completing trials featuring combinations of assistance modes, target distances, and target orientations. The second study was similar to the first but included an extended training module. Their work concluded that trials involving haptic assistance (virtual fixturing and shared-control) revealed improvements in user performance than non-haptic treatments.

2.5.3 Manual Assembly

Adams et al. (2001) investigated haptics-based interaction for performing manual assembly tasks within a virtual environment. Their user study involved three treatments: virtual training with force feedback and without force feedback, and no virtual training. During virtual training, participants used one hand to control an Excalibur Force Display. The assembly sequence featured a biplane model of LEGO™ components. The study required users to perform their respective training methods followed by five iterations of a real assembly. The researchers concluded that participants who received virtual training with haptic feedback completed trials in less times than users who did not receive training. Their work found no significant difference in performance between participants who received either form of the virtual training.

Bloomfield et al. (2003) formulated a taxonomy of haptic actions required in performing virtual disassembly tasks. To examine the influence of haptic feedback, researchers compared user performance in disassembling an F-16 aircraft fuel tank. The study included three interactive devices: a SpaceMouse™, a CyberGlove™, and a PHANToM™ device. Only the PHANToM™ device was capable of rendering haptic feedback to users. The investigators observed that the participants completed the disassembly sequence in less time when using the PHANToM™ device (57.98 seconds) than the SpaceMouse™ (89.27 seconds) and the CyberGlove™ (96.81 seconds).

In 2004, researchers (Edwards et al. 2004) examined the use of haptic and auditory cues for performing assembly and disassembly procedures within a virtual environment. The researchers were interested in determining if auditory cues were a viable substitution for haptic feedback. Their work included a study with 24 participants completing assembly sequences using four sensory methods: auditory, haptics, auditory with haptics, and visuals-only. Their research concluded that trials featuring haptic or auditory feedback required greater amounts of time than trials using visual perception. The researchers also observed that force rendering had a significant effect on the number of detected collisions in assembling components.

CHAPTER 3. USER STUDY

3.1 Introduction

In order to investigate the effect of haptic-based interaction in the virtual assembly, a user study is designed and approved by Iowa State University's Institutional Review Board. This authorization process ensured the ethical nature of the investigation in terms of risks, benefits, and all methods of evaluation that would affect the targeted sample population. The user study involved two stages: a preliminary and final investigation. The intent of the preliminary investigation was to validate test procedures and to identify areas of improvement in the study. After addressing the necessary modifications, the final investigation involved a larger sample population.

3.2 VR Application

This research included the development of a software application that integrated haptics-based interaction with rigid body dynamics in a virtual reality simulation. The goal was to evaluate user performance with haptics-based interaction in performing assembly tasks in a virtual simulation. The application was written in C++ language in an object oriented programming context and consists of three dedicated threads for rendering graphics, haptics, and physics.

3.2.1 Software

The user study application is based on VR Juggler, an open source package developed at Iowa State University (Cruz-Neira et al. 2005). VR Juggler framework is comprised of modular components that handle a variety of VR hardware devices and software components.

For instance, VR Juggler's Gadgeteer module manages input devices such as positional tracking systems. The Juggler Configuration and Control Library (JCCL) contain a collection of configurations and tools for monitoring software performance. The Tweek module allows developers to specify different graphical user interface configurations. VR Juggler also incorporates the Graphics Math Template Library (GMTL) for performing calculations.

The physics-based modeling is implemented on Ageia's PhysX SDK™ v2.4.4 (2006). The toolkit simulates rigid body dynamics using the penalty-based method at a minimum update rate of 60 Hz. PhysX™ offers several important features for developing realistic simulations including collision detection, modeling of part interaction, and an ability to handle concave triangular mesh geometry. PhysX also supports modeling of different kinematic joints (NxJoint) that constrains individual degrees-of-freedom for actors (NxActor) within the simulation.

PhysX is capable of performing collision detection and physics simulation for complex CAD models using *penetration maps*. This programming structure (NxPMap) represents the triangular mesh geometry in voxelized form at a user-defined resolution. For each virtual assembly component, the respective triangle mesh data assists in defining an actor (NxTriangleMesh) in the simulation. The mesh actor object is then passed as a parameter into a function, NxCreatePMap(), that returns a corresponding collision model. The resulting data is written and stored to an external file (*.pmap) to facilitate future use without the initial preprocessing step.

To allow users to select and manipulate virtual components, the application implements a virtual coupling, a spring and damper system that connects a user-controlled virtual cursor to a selected component. PhysX provides a joint class, NxD6Joint, which allows programmers define spring and damping parameters along each of the six degrees of freedom. The spring force is calculated and sent to haptic device for rendering.

To provide haptic rendering, the user study application integrates SensAble Technologies OpenHaptics™ toolkit. The toolkit provides two API's that provide different levels of programming access to developers; Haptics Library API (HLAPI) and Haptics Device Library (HDAPI). The HDAPI was utilized for the software development since it provided low-level access to the haptic device (Sensable Technologies 2005). Programming for haptic device operates based on a scheduler that maintains a high frequency (~1000 Hz), high priority thread. The scheduler handles the execution of callback functions for sending computed force quantities and retrieving device state information at interactive rates.

Figure 3.1 depicts the virtual assembly application's infrastructure. The infrastructure consists of two aspects in executing the program: initialization and runtime. The application startup involves the initialization of the haptic devices and scheduler using OpenHaptics function calls. For each assembly component, two files are loaded in the application: an *.obj file and a *.pmap file for graphical visualization and physics calculation respectively. The runtime phase consists of the core of the application and user interaction. The core of the program involves three independent threads that perform updates for haptics, physics, and graphics. Haptics and physics threads communicate state information of virtual objects in a bidirectional manner. Updates pertaining to scene visualization are dependent on state information obtained from both the haptic and physics threads. In terms of user interaction, the software application permits input through mouse, keyboard, and haptic devices. Three-dimensional graphics visualization and haptic feedback provide users with sensory information from the virtual simulation.

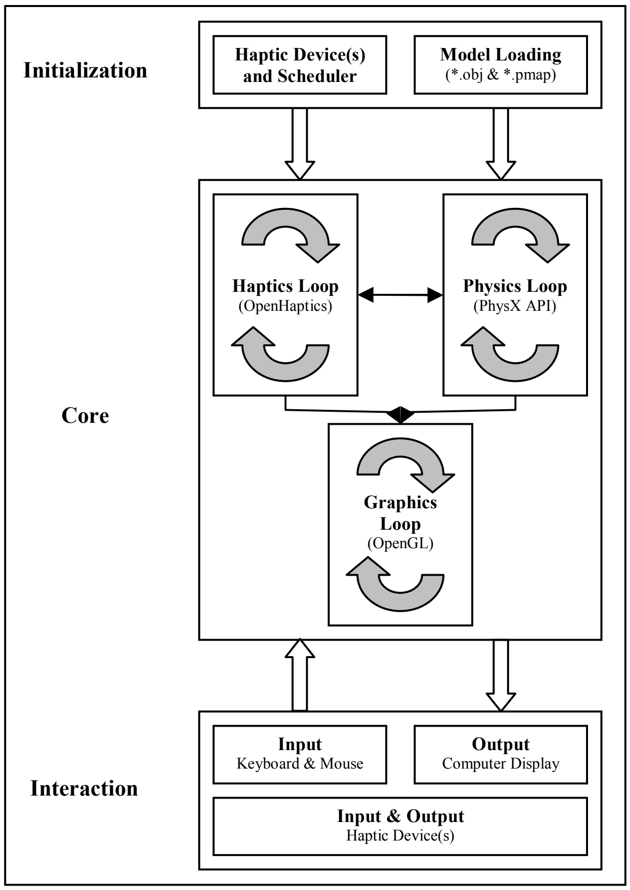

Figure 3.1. Virtual assembly application infrastructure

3.2.2 Hardware

The software application was tested on a Windows™ workstation that featured an Intel Xeon™ 3.06 GHz processor, 1.0 GB of RAM, and a NVIDIA Quadro™ FX 1000 graphics card with 128 MB dedicated memory. The display involved a rear-projected system comprised of an InFocus DepthQ™ DQ3120-A stereoscopic projector and a 30-inch Graybow Glasfire™ screen. Graphics rendering was set at a screen resolution of 800 by 600 pixels with a 120 Hz refresh rate.

The use of specialized equipment allowed participants to experience an immersive VR simulation. This included stereoscopic viewing using Crystal Eyes™ shutter glasses synchronized with a Stereographics™ emitter, and head tracking using a Polhemus Patriot™ electromagnetic system with a position sensor mounted to the side of the shutter glasses. This setup allowed users to adjust the viewing perspective based on head motions.

The system utilizes two PHANToM™ Omni devices arranged in a dual-handed configuration. These mechanisms are cost effective and are able to render three-dimensional haptic feedback. The Omni model can exert a maximum force of 3.3 N (0.75 lbf.) at nominal positions and can render a continuous force of 0.88 N (0.2 lbf.). The device features three-dimensional position tracking using digital encoders and provides a workspace of 6.4 x 4.8 x 2.8 inches. The tracking of stylus orientation is accomplished through potentiometers (Sensable Technologies 2007). Figure 3.2 depicts the configured virtual reality system used during the user study investigation.

Figure 3.2. Hardware setup for immersive virtual reality system

3.3 Framework

The framework of the user study consists of three phases. The introductory phase involved participants completing a pre-study questionnaire regarding demographics along with relevant experiences. Users also received an overview of the study and a hands-on demonstration of hardware and software application. Subjects were given time to become familiar with the haptic device's workspace and range of input.

The second phase of the user study involved subjects performing three experiments including weight recognition, part positioning, and assembly simulation. The presentation of each experiment involved a discussion covering the motivation, task procedures, the methods of performance evaluation, and the different experimental variations. Users proceeded through the study and performed a series of trials within each of the assembly-related experiments. The final phase of the user study investigation required subjects to complete a post-study questionnaire about levels of comfort in performing the experiments, the usability of the haptic devices, and the effectiveness of the simulation.

3.4 Preliminary Investigation

The preliminary study involved a sample population of eleven students from Iowa State University. Their ages ranged from 21 to 28 years old with a median of 25. Only one individual indicated left hand dominance. The majority (63.6%) of the sample population had prior experiences with haptic interfaces through demonstrations, academic research, or from similar equipment including video game controllers. In addition, 54.5% of users indicated previous experience in performing assembly operations including computer hardware installation and in using CAD software such as Pro/Engineer.

Each subject proceeded through the user study according to the framework defined in section 3.3. One issue observed during the pilot study concerned the randomization of trials within each experiment. The sequence of trials was determined based on random presentation of haptic and non-haptics sensory methods and did not account for additional experimental factors. This issue was resolved for the final investigation.

3.5 Final Investigation

The final study involved 29 participants from Iowa State University and 15 engineers from industry. Due to the uneven number of subjects between groups, subjects were evaluated as one sample population. From the original 44 participants, the results of four individuals were removed from the data analysis due to external sources of variation during testing including interruptions or significant knowledge of the research that could influence their performance.

The sample population featured 6 females and 34 males with ages ranging from 18 to 58 years of age (median of 24, mean of 27.2 $\pm$ 9.5). The ages of the entire sample demonstrated a right-skewed distribution with the majority of participants being of younger age. Figure 3.3 illustrates the distribution of the sample population.

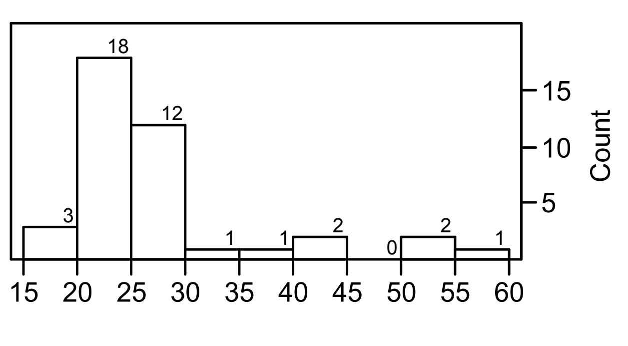

Figure 3.3. Histogram plot of age

Nine participants specified having an engineering profession and featured a mean age of 38.4 $\pm$ 13.5 years old. Twelve individuals were graduate research assistants with a mean age of 25.6 $\pm$ 2.4 years old. Eighteen subjects were undergraduate students with a mean age of 21.8 $\pm$ 2.7 years old. One individual, 42 years old, listed clerical as their field of work. Of the forty participants, two individuals indicated left hand dominance.

The majority of the sample population (75%) indicated that they had prior assembly experience. Additional responses indicated that participants were assembly engineers, have assembled consumer products, and have completed assemblies using CAD software. Subjects were also required to specify their past exposure to haptic devices. A larger percentage (72.5%) of the individuals did not have any previous knowledge of haptics-based interaction, while 27.5% had exposure from using haptic devices or video game controllers. In conducting the final investigation, the sample population performed the three experiments in accordance to the framework outlined in section 3.3.

3.6 Data Analysis

Details of the three experiments and results are presented in Chapters 4, 5, and 6. Each experiment featured a randomized complete block design. Each individual performs all trials in randomized sequences without replication. The data for each participant was analyzed as a set in order to minimize error between subjects. The randomized complete block design was used to examine the difference in treatment means for a particular effect (Ott and Longnecker 2001). For the analysis of each performance measurement, the hypothesis test considers a null statement where all mean values for levels of an effect are equivalent. The alternative hypothesis estimates that at least one mean value was statistically different from the remaining quantities:

$$\begin{gathered} H_o : \mu_1 = \mu_2 = \mu_3 \ldots = \mu_t \\ vs. \\ H_a : \text{At least one } \mu_i \text{ differs from the rest} \end{gathered} \tag{3.1}$$

Once data collection was completed, mean tables were constructed to summarize and contrast the different levels within a particular variable. An overall mean value was computed for each table to depict the average performance resulting from the variable. The distribution of data for each variable was illustrated using a box plot diagram. This graphical method summarizes the data set in terms of quartiles and assists in identifying the skew points of the data set.

After summarizing the performances observed during the current investigation, data values were examined using *ANOVA* (analysis of variance). This method evaluates the sources of variability in the designed study and their statistical significance. An *Effect Tests* table was included to proportion the *ANOVA*'s *Model* source by all variations in the experiment as individual and combined effects (SAS 2005). The statistics obtained from the *Effect Tests* assist in evaluating the hypothesis test (equation 3.1) for a variation source. An *F-ratio* was calculated for each effect by dividing the respective *Mean Square* by the estimate of error variance given by the *Mean Square Error*. A probability, *p-value*, was computed and reflected the likeliness of obtaining a larger *F-ratio*. A significance level (α) of 0.05 was stipulated to determine the statistical significance of the source of variability. The significance level was selected since the designed study did not warrant a restricted value of 0.01 that is more commonly found in medical studies (Ott and Longnecker 2001). If the computed *p-value* was less than the α-level, the experimental factor was assessed as being a significant source of variation on the resulting performance measurements.

CHAPTER 4. WEIGHT RECOGNITION EXPERIMENT

4.1 Introduction

The weight of a component is critical in planning for parts handling due to ergonomic factors (Boothroyd 2005). Objects of considerable size and weight (i.e. engine block) require hoists or fixtures to assist in positioning the component within the assembly. Small objects such as bolts, nuts, and screws are light enough that the assembly workers can operate using a single hand. Within a virtual environment, interpreting the mass of an object using just visual sensory cues can be difficult and lead to incorrect assumptions. Virtual objects of larger volume are not guaranteed to be heavier than small parts with greater densities. The addition of haptics-based interaction provides a means of higher fidelity in interpreting the object weight.

4.2 Hypotheses

The primary hypothesis of this study is that in a digital simulated environment, haptic interaction will assist users in distinguishing weight properties of objects more intuitively than visual information alone. Haptic rendering will result in less completion times and a higher accuracy in performing weight comparisons and gravitational force quantities.

The investigators also hypothesize that subjects will distinguish paired virtual objects more accurately and in less time when the difference in mass properties is greater. The subjects are anticipated to perform the weight recognition tasks more efficiently when controlling the heavier object with their dominant over non-dominant hand.

4.3 Experimental Procedures

The objective of this experiment is to observe users in performing a weight recognition task. Each trial featured paired virtual objects of similar shape and size, but with different mass properties. Models were identified based on color; red for objects on the right side of the environment and blue for objects on the left. These assigned colors corresponded with the virtual cursors that represented the haptic devices' end effecter in the simulation. Participants manipulated the virtual objects with the color-coordinated device and observed the objects' physical responses. Using the sensory information provided in the trial, participants were required to identify the heaviest object.

4.3.1 Experimental Factors

Variations in the perception of weight served as the primary experimental factor. For the trials that did not include force rendering, participants observed the physical nature of the dynamic objects using only visual perception. This included monitoring the effects of gravity, contact, and friction forces on the manipulated components. For trials that included force rendering, the participants were able to feel the weight forces.

The second experimental factor involved the mass relationship between the paired objects. There were three distinct ratios in the weight recognition experiment. A weight ratio of 1:1 served as a control to determine if participants were capable of detecting equally weighted models. Two ratios (2:1 and 3:1) provided weight differences between the paired virtual models.

The final experimental factor concerned which hand was manipulating the heaviest object. In all trials, subjects were required to use both hands to manipulate the paired virtual models. Subjects controlled the heaviest object with either their dominant or non-dominant hand.

4.3.2 Experiment Structure

The weight recognition experiment featured a randomized complete block design. Each participant completed ten trials consisting of factorial combinations of mass ratio, sensory rendering, and active hand. Subjects performed the trials in randomized sequences without replication. Table 4.1 defines all ten trials based on the combinations of experimental factors.

Table 4.1. Weight recognition experiment trials

Trial	Mass Ratio	Hand	Rendering
1	2 to 1	Dominant	Non-Haptics
2	2 to 1	Non-Dominant	Non-Haptics
3	3 to 1	Dominant	Non-Haptics
4	3 to 1	Non-Dominant	Non-Haptics
5	1 to 1	--	Non-Haptics
6	2 to 1	Dominant	Haptics
7	2 to 1	Non-Dominant	Haptics
8	3 to 1	Dominant	Haptics
9	3 to 1	Non-Dominant	Haptics
10	1 to 1	--	Haptics

4.4 Performance Evaluation

Performance was evaluated based on two criteria: time of completion in seconds and accuracy of weight difference determination. Subjects could use as much time as they needed before responding. Participants had to state which of the two objects was heaviest. The instructions indicated that the heaviest object could occur in either hand or the weights could be equivalent.

4.5 Data Analysis

The data analysis involved examining the performance of forty participants in completing the weight recognition experiment. The use of mean tables summarizes user performance for each level of variation. The first two tables organized mean values based on sensory method. The third and fourth tables examined the mean values for trials involving a 2:1 and 3:1 mass ratio, respectively. The final two tables arranged mean values based on active hand control. The summary process also involved graphical evaluation through box plot comparisons. This provided an opportunity to observe the distribution of measurements between the levels within each experimental factor.

Statistical analysis using an ANOVA procedure evaluated the significance of each source of variation on the obtained measurements. Since the experiment involved three factors, an *Effect Tests* table proportioned the *Model* source of variation. Based on the computed test statistics, the statistical significance of each experimental factor was determined.

4.5.1 Completion Time

The first aspect of evaluating performances during the weight recognition experiment concerned the amount of time participants required to complete the weight recognition tasks.

Table 4.2. Table for mean times in haptics trials

Haptics	2:1	3:1	Hand Avg.
Dominant	28.265	24.251	26.258
Non-Dominant	31.239	22.855	27.047
Ratio Avg.	29.752	23.553	26.653

Table 4.2 contrasts mean completion times for trials that included haptic feedback during the weight recognition experiment. The sample population performed the haptics-assisted trials with a mean time of 26.653 $\pm$ 14.117 seconds. Table 4.3 summarizes the trials that provided only visual information. A mean time of 29.171 $\pm$ 18.468 seconds was required to perform each of the non-haptics weight recognition trials.

Table 4.3. Table for mean times in non-haptics trials

Non-Haptics	2:1	3:1	Hand Avg.
Dominant	35.283	28.716	32.000
Non-Dominant	28.789	23.893	26.341
Ratio Avg.	32.036	26.305	29.171

The measurements obtained from the sample population indicate contradicting results in terms of central tendency. The mean values demonstrate that participants required less time to evaluate the paired virtual models when weight forces were rendered. However, the median completion time for the non-haptics trials was 22.190 seconds while the haptics trials required 22.929 seconds. Time values for trials presenting only visual cues demonstrated a larger variance in measurements (341.081) than the haptics-based approach (199.306).

Figure 4.1 depicts the distribution of time measurements between the two sensory methods. Based on the two mean tables and the graphical statistics, variations in force rendering did not appear to affect completion times in performing the weight recognition experiment.

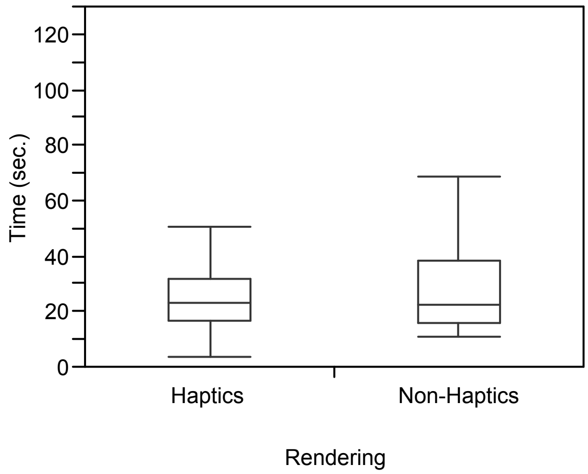

Figure 4.1. Box plot comparison of times based on sensory method

Table 4.4. Table for mean times in 2:1 trials

2:1	Haptics	Non-Haptics	Hand Avg.
Dominant	28.265	35.283	31.774
Non-Dominant	31.239	28.789	30.014
Rend. Avg.	29.752	32.036	30.894

Table 4.4 summarizes mean completion times for trials with mass ratio of 2:1. In performing the four trials, subjects took a mean of 30.894 $\pm$ 18.982 seconds to distinguish the weight quantities. Table 4.5 compares the mean completion times for trials with a mass ratio of 3:1. The result shows a mean time of 24.929 $\pm$ 12.859 seconds for these trials.

Table 4.5. Table for mean times in 3:1 trials

3:1	Haptics	Non-Haptics	Hand Avg.
Dominant	24.251	28.716	26.484
Non-Dominant	22.855	23.893	23.374
Rend. Avg.	23.553	26.305	24.929

A comparison of mean values indicated that participants were capable of distinguishing paired models in less time for trails with a mass ratio of 3:1. The median values demonstrated this trend; 20.320 versus 24.4766 seconds for the 3:1 and 2:1 ratios, respectively. Time measurements obtained from 2:1 trials demonstrated greater variation in measurements (360.316) than the 3:1 trials (165.353). Figure 4.2 contrasts the distribution of each data series. The researchers assumed that the difference in mass property between paired objects affects weight recognition times.

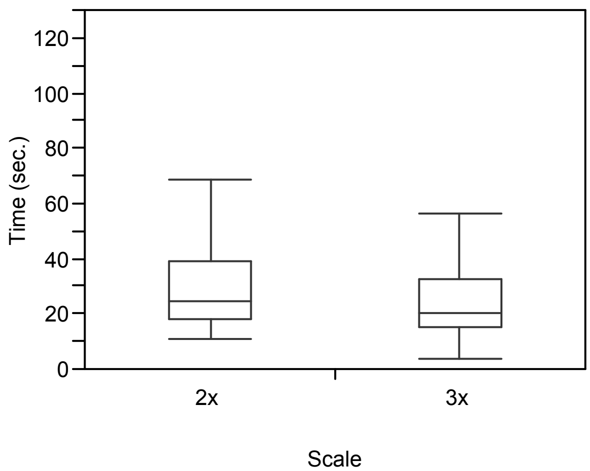

Figure 4.2. Box plot comparison of times based on mass scale

The final set of mean tables examines completion times based on active hand. During the eight trials, each hand manipulated the heavier object in four procedures. Table 4.6 outlines the mean time of completion for trials that featured the heaviest object manipulated by the dominant hand. Participants required a mean time of 29.129 $\pm$ 18.202 seconds to identify the heavier virtual object when was controlled by the dominant hand.

Table 4.6. Table for mean times in dominant hand trials

Dominant	Haptics	Non-Haptics	Ratio Avg.
2:1	28.265	35.283	31.774
3:1	24.251	28.716	26.484
Rend. Avg.	26.258	32.000	29.129

Table 4.7. Table for mean times in non-dominant hand trials

Non-Dominant	Haptics	Non-Haptics	Ratio Avg.
2:1	31.239	28.789	30.014
3:1	22.855	23.893	23.374
Rend. Avg.	27.047	26.341	26.694

Table 4.7 contrasts the mean completion time for trials that featured non-dominant hand control of the heavier model. An overall mean time of 26.694 $\pm$ 14.466 seconds was required to complete the four trials.

The mean values indicated that trials featuring non-dominant hand control of the heavier object required less time than the dominant hand trials. The median times for hand control also confirmed this notion; 21.913 for non-dominant hand and 22.984 seconds for dominant hands. Data values pertaining to dominant hand use revealed higher variation between measurements, indicated by a variance of 331.312 for the dominant hand measurements and 209.282 for the non-dominant.

Figure 4.3 demonstrates the distributions for both data series. The measurements collected from the sample population indicated that controlling the heaviest object with dominant or non-dominant hand had minimal influence on completion times during the weight recognition experiment.

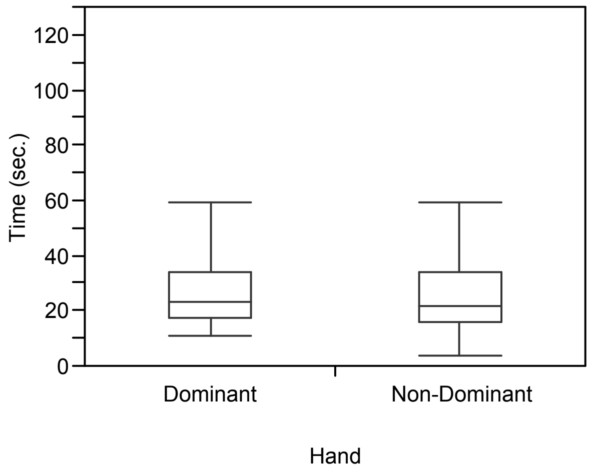

Figure 4.3. Box plot comparison of times based on hand usage

After summarizing the completion times, *ANOVA* was used to determine the statistical significance of the sources of variation within the experiment. An additional *Effect Tests* table portioned the *Model* source of variation by the experimental factors. Tables 4.8 and 4.9 outline the results of the *ANOVA* procedure and the Effect Tests, respectively.

Table 4.8. ANOVA for time measurements

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	46	34538.620	750.840	3.9502
Error	273	51890.480	190.075	Prob > F
C. Total	319	86429.100		<.0001

Table 4.9. Effect tests for time measurements

Source	DF	Sum of Squares	F Ratio	Prob > F
Subject	39	29656.072	4.0006	<.0001
Scale	1	322.244	1.6954	0.1940
Hand	1	176.839	0.9304	0.3356
Rendering	1	984.992	5.1821	0.0236
Scale*Hand	1	190.934	1.0045	0.3171
Scale*Rendering	1	65.157	0.3428	0.5587
Hand*Rendering	1	896.257	4.7153	0.0308
Scale*Hand*Rendering	1	182.411	0.9597	0.3281

Variations in sensory modalities were determined to have a significant effect on completion times (*F-ratio* = 5.1821, *p-value* = 0.0236). In five of the six mean tables, procedures that rendered gravitational forces required less time to perform. This concluded that haptics-based interaction could be effective in reducing performance times for weight comparison tasks.

The variations in mass ratios between paired objects did not effect performance times during the weight recognition experiment (*F-ratio* = 1.6954, *p-value* = 0.1940). From an *F-ratio* of 0.9304 and a *p-value* of 0.3356, variations in hand control were determined to be statistically insignificant. Measurements obtained from the sample population revealed minimal differences between completion times in dominant and non-dominant hand use.

The *ANOVA* procedure indicated that combinations of active hand and rendering factors had a significant influence on performance times (*F-ratio* = 4.7153, *p-value* = 0.0308). This infers that performance times were dependent on which hand was controlling the heaviest object and the method of presenting sensory information.

4.5.2 Response Accuracy

The second aspect of evaluating performance during the weight recognition experiment concerned the accuracy of participants in identifying the heaviest object. Table 4.10 summarizes the mean response accuracy for trials that rendered weight forces. Subjects were capable of accurately detecting the greater weight at a mean of 78.1 $\pm$ 41.4% when haptic feedback was included.

Table 4.10. Table for mean accuracy in haptics trials

Haptics	2:1 (10:5 kg)	3:1 (15:5 kg)	Hand Avg.
Dominant	0.600	0.850	0.725
Non-Dominant	0.725	0.950	0.838
Ratio Avg.	0.663	0.900	0.781

Table 4.11 contrasts the mean accuracy of users in trials that provided only visual information. Subjects correctly identified the heaviest object at mean percentage of 51.9 $\pm$ 50.1 in the non-haptics trials.

Table 4.11. Table for mean accuracy in non-haptics trials

Non-Haptics	2:1	3:1	Hand Avg.
Dominant	0.525	0.600	0.563
Non-Dominant	0.375	0.575	0.475
Ratio Avg.	0.450	0.588	0.519

Trials that included force feedback produced a greater mean percentage of correct responses than the non-haptics procedures. The median value of accuracy for each data series was equivalent to 100.0%. The non-haptic data series conveyed a higher amount of variation (2512.1) between measurements than the haptic procedures (1719.7). The measurement results indicate that the subjects were capable of identifying the heaviest virtual object with higher accuracy when using haptic feedback.

Table 4.12. Table for mean accuracy in 2:1 trials

2:1	Haptics	Non-Haptics	Hand Avg.
Dominant	0.600	0.525	0.563
Non-Dominant	0.725	0.375	0.550
Rend. Avg.	0.663	0.450	0.556

The second evaluation of response accuracy focuses on variations in implemented mass ratios. Table 4.12 and Table 4.13 reports the mean accuracy scores of users in trials that involved paired objects defined using a 2:1 and 3:1 mass ratio respectively. The experimental data shows that subjects were capable of detecting the heaviest object with an accuracy of 55.6 $\pm$ 49.8% and 74.4 $\pm$ 43.7% for paired objects with mass ratio 2:1 and 3:1 respectively.

Table 4.13. Table for mean accuracy in 3:1 trials

3:1	Haptics	Non-Haptics	Hand Avg.
Dominant	0.850	0.600	0.725
Non-Dominant	0.950	0.575	0.763
Rend. Avg.	0.900	0.588	0.744

It can be concluded that participants were able to identify the heaviest object more accurately and less variation (1917.8) for the 3:1 mass ratio. Both data series had similar median values of 100.0%. Based on the measures of central tendency, variations in mass ratios appeared to have influenced the percentages of correct responses during the weight recognition experiment.

Table 4.14. Table for mean accuracy in dominant hand trials

Dominant	Haptics	Non-Haptics	Ratio Avg.
2:1	0.600	0.525	0.563
3:1	0.850	0.600	0.725
Rend. Avg.	0.725	0.563	0.644

The last experimental factor in which accuracy scores were evaluated concern variations in active hand. Table 4.14 contrasts the mean percentage of correct responses for trials that involved participants controlling the heaviest object with their dominant hand. The mean accuracy for the four dominant hand trials was 64.4 $\pm$ 48.0%. The final mean table (Table 4.15) summarizes the mean accuracy of response for trials that featured non-dominant hand control of the heaviest object. Subjects demonstrated an overall accuracy of 65.6 $\pm$ 47.6% during these trials.

Table 4.15. Table for mean accuracy in non-dominant hand trials

Non-Dominant	Haptics	Non-Haptics	Ratio Avg.
2:1	0.725	0.375	0.550
3:1	0.950	0.575	0.763
Rend. Avg.	0.838	0.475	0.656

Variations hand control revealed minimal differences in accuracy scores. For both dominant and non-dominant hands, participants correctly identified the heaviest object with similar mean percentages. Each series had a median accuracy score of 100.0%. Data values for each method had comparable variances in measurements; 2269.5 and 2307.7 for non-dominant and dominant hand control. It can be concluded that variations in active hand had a minimal effect on users' ability to identify the heavier of paired objects.

An *ANOVA* procedure (Table 4.16) assisted in determining the statistical significance of each source of variation. An additional *Effect Tests* (Table 4.17) proportioned the *Model* source of variation by the experimental factors.

Table 4.16. ANOVA for accuracy percentages

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	46	24.300000	0.528261	2.9735
Error	273	48.500000	0.177656	Prob > F
C. Total	319	72.800000		<.0001

Table 4.17. Effect tests for accuracy percentages

Source	DF	Sum of Squares	F Ratio	Prob > F
Subject	39	14.800000	2.1361	0.0002
Scale	1	1.250000	7.0361	0.0085
Hand	1	0.312500	1.7590	0.1859
Rendering	1	0.112500	0.6332	0.4269
Scale*Hand	1	0.006250	0.0352	0.8514
Scale*Rendering	1	0.306250	1.7238	0.1903
Hand*Rendering	1	0.756250	4.2568	0.0400
Scale*Hand*Rendering	1	0.112500	0.6332	0.4269

As an independent variable, the use of haptic and non-haptic sensory rendering had an insignificant effect on user accuracy (*F-ratio* of 0.6332, *p-value* = 0.4269). However, the analysis indicated that the combined effect of active hand and sensory rendering factors was statistically significant (*F-ratio* = 4.2568, *p-value* = 0.0400). This infers that the correct identification of objects was dependent on which hand was controlling the heavier object and the type of sensory modality.

From a test statistic of 1.7590 and a *p-value* of 0.1859, variations in hand control as an independent effect was determined to be statistically insignificant. However, the applied mass ratio between paired models was determined to be a significant source of variation in the study. An *F-ratio* of 7.0361 and a *p-value* of 0.0085 indicate that subjects were able to detect the heavier object more accurately when paired models were defined using a 3:1 mass ratio than the 2:1 baseline.

4.5.3 User Preference

Upon the completion of the weight recognition experiment, the sample population answered three questions regarding the ten procedures. The first asked users about their level of comfort in selecting the heaviest virtual model during the non-haptics trials. The second question was similar to the first but concerned trials that involved rendering of gravitational forces. Figure 4.5 contrasts the responses for each question.

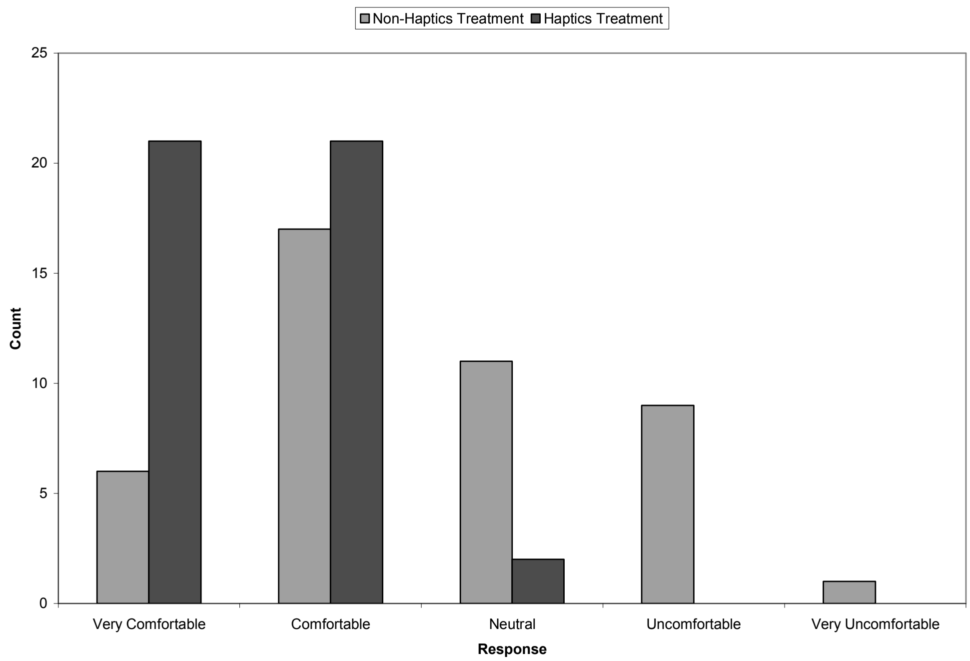

Figure 4.5. User level of comfort in non-haptics and haptics treatments

For the non-haptics trials, the majority of participants (38.6%) felt *Comfortable* in performing the weight recognition experiment with only visual cues. An additional 25.0% of users were *Neutral* in their response while 22.7% indicated feeling either *Uncomfortable* or *Very Uncomfortable*. In responding to this question, 13.6% expressed a high level of comfort in identifying the heaviest component through visual perception.

For the haptics-enabled trials, equal portions (47.7%) of the sample population felt either *Very Comfortable* or *Comfortable* in comparing weight forces. The remainder of the sample population, 4.5%, indicated a *Neutral* response. None of the users felt uncomfortable during the haptics-based procedures.

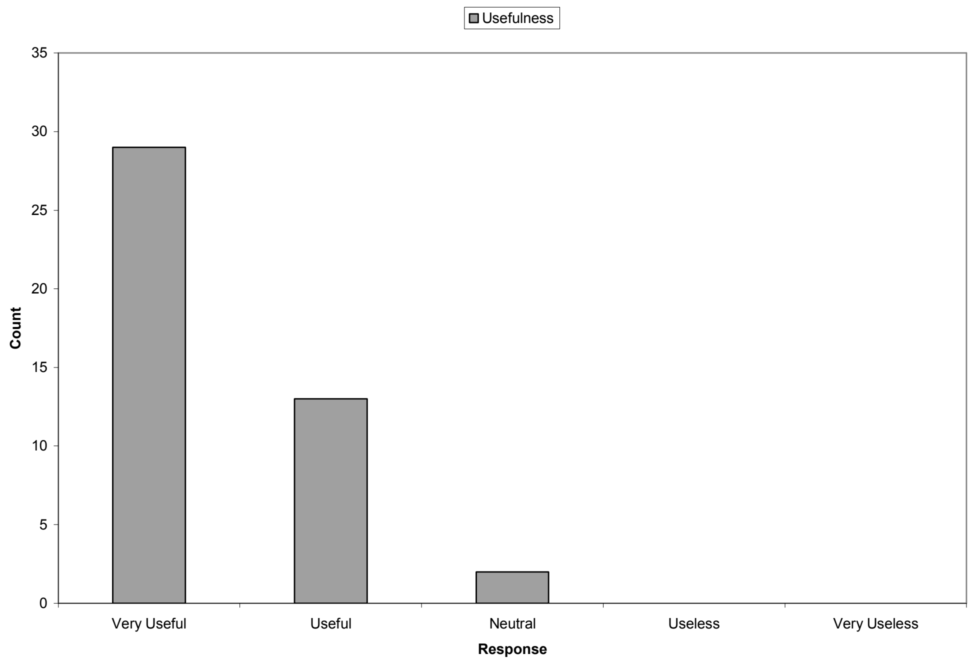

Figure 4.6. Force feedback usefulness for weight recognition experiment

The third question involved participants indicating the usefulness of haptic feedback during the weight recognition experiment (Figure 4.6). The majority (65.9%) of the sample population indicated that haptics-based interaction was *Very Useful* for distinguishing weight forces between paired objects. An additional 29.5% viewed haptic feedback as *Useful*, while the remaining users where *Neutral*. No one from the sample population assessed haptic feedback as *Useless*.

4.6 CONCLUSION

The objective of the weight recognition experiment was to examine the performance benefits associated with haptics-based interaction. The hypotheses of this experiment are that haptic force feedback can benefit the weight recognition by (1) a reduction in evaluation times and (2) higher accuracy in identifying the heavier object.

The experimental results were analyzed using *ANOVA* and agreed with the hypothesis concerning evaluation times. More specifically, the rendering of gravitational forces resulted in lower completion times when users performed the designed weight recognition experiment. The statistical analysis also determined the presence of interaction between hand control and sensory methods. This shows that completion times were significantly dependent on which hand was manipulating the heavier object and the type of sensory modality.

With regard to the second hypothesis of accuracy of in identifying the heavier component, trials show an accuracy of 78.1% when haptic force feedback is present. This accuracy is better than the accuracy of 51.9% for the case when haptic force feedback is not provided. This concluded is again drawn based on statistical evaluation using *ANOVA*. However, the analysis of variance procedure attributed a significant influence from interactions between active hand and sensory factors on the resulting accuracy percentages. The accuracy of was dependent on which hand was controlling the greater massed virtual object and the sensory modality used.

The evaluation concluded that the scaling of mass ratios between the paired virtual components was the most influential factor on user accuracy. Trials that featured models with mass quantities defined by the 3:1 baseline resulted in a higher percentage (74.4%) of accurate responses than trials involving the 2:1 mass relationship (55.6%). The statistical evaluation did not assign significant effects to the other sources of variation in the experiment.

CHAPTER 5. PART POSITIONING EXPERIMENT

5.1 Introduction

One fundamental aspect of the assembly process is the positioning of components with respect to other parts. In performing teleoperation tasks, the physical and corresponding virtual workspaces must provide the user with the same degrees of freedom in order to present a realistic simulation. Compared to 2D mouse, a benefit of haptic devices is their three-dimensional workspace. Users must not be encumbered by the device (Massie and Salisbury 1994) and be able to position a digital assembly component at any desired location within the virtual workspace. This chapter will present user study for the task of positioning components within a virtual environment.

5.2 Hypotheses

The primary hypothesis for this study is that haptic-based interaction will enable users to position objects within a three-dimensional simulated environment more proficiently than using only visual perception. The investigators hypothesize that force rendering will allow users to complete positioning trials in less time. In addition, haptic feedback will permit users to interpret contact forces that assist in placing a virtual object at its final location. This has been observed in several scholarly endeavors that examined user performance with regard to contact between virtual objects (Magnusson et al. 2002; Jones et al. 2005). The researchers also estimate that the rendering resistive forces will enable users to displace an object more steadily than teleoperation tasks that do not include the assistance of haptics.

The study will examine variations in translational direction. The researchers anticipate that displacements along the z-direction will present a unique challenge to many of the subjects. These trials require participants to rely on their perception of depth within the virtual simulation. The experiment also considers the performance effect associated with dominant and non-dominant hand usage. The purpose of this is to evaluate the usability of the haptic device with each hand. The investigators hypothesize that the sample population will produce contrasting measurements based on hand-dominancy.

5.3 Experimental Procedures

The primary objective of the experiment is to find out whether or not the haptic feedback is beneficial in controlling the position of a virtual object. Starting at an initial location, subjects are required to steadily translate a movable virtual model along a specified trajectory until it has assembled with a static object. Trials involved factorial combinations of sensory rendering, translational direction, and active hand.

5.3.1 Experimental Factors

The primary experimental factor is variations in the sensory perception. Two treatments are carried out to determine the usefulness of haptic force feedback in positioning objects. In the first treatment, users performed the teleoperation without the aid of haptic forces and were required to observe contact between objects using visual interpretation. In the second treatment, the users experienced resistive forces to ensure steady translation and contact forces upon placing the object at its target location.

The secondary experimental factor is the translational direction. The displacement of the movable part occurred along a target direction with the remaining degrees of freedom constrained. Input to the haptic devices affected the virtual component only along the target direction. Table 5.1 shows the relationships between the free and constrained directions used during the part positioning experiment.

Table 5.1. Target and constrained directions scenarios in the experiment

Target Direction	Constrained Direction #1	Constrained Direction #2
X-Direction	Y-Direction	Z-Direction
Y-Direction	X-Direction	Z-Direction
Z-Direction	X-Direction	Y-Direction

During the actual teleoperation procedure, participants must control the device while minimizing movements along the constrained directions. Afterwards, users released the virtual object at the target position. Figure 5.1 demonstrates a positioning task along the x-direction.

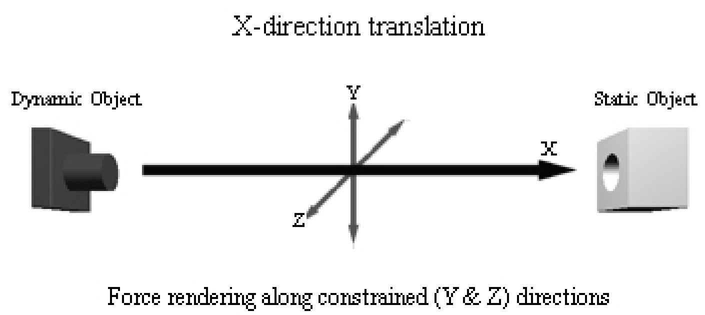

Figure 5.1. Target and constrained directions scenario in the experiment

The third experimental factor is hand control. Many real assembly sequences require the positioning of objects using either hand to complete a particular operation. Subjects were required to use either their dominant or non-dominant hand to translate the movable object in the VR simulation.

5.3.2 Experiment Structure

Table 5.2 defines twelve trials based on combinations of experimental factors including sensory rendering, translational direction, and active hand. The structure of the experiment featured a randomized complete block design. Each participant performed the trials in individually random sequences without replication. Subjects were instructed which hand to use, the translational direction, and the sensory modality.

Table 5.2. Part positioning experiment trials

Trial	Direction	Hand	Rendering
1	X	Non-Dominant	Non-Haptics
2	Y	Non-Dominant	Non-Haptics
3	Z	Non-Dominant	Non-Haptics
4	X	Dominant	Non-Haptics
5	Y	Dominant	Non-Haptics
6	Z	Dominant	Non-Haptics
7	X	Non-Dominant	Haptics
8	Y	Non-Dominant	Haptics
9	Z	Non-Dominant	Haptics
10	X	Dominant	Haptics
11	Y	Dominant	Haptics
12	Z	Dominant	Haptics

5.4 Performance Evaluation

The user performance is evaluated by three criteria: completion time, target error, and average path deviation. Subjects can use as much time as they need to complete the teleoperation. The target error measures the users' ability to place objects at specified (final) locations within the three-dimensional environment. The position of the movable object's local origin with respect to the VE's coordinate system was recorded throughout the entire process. A three-dimensional displacement vector was computed using the coordinates of the virtual object's final position, P_a, and the trial's target location, P_t. The magnitude of the vector indicated a measure of target error, E_t, for placement accuracy (Equation 5.1). A target error value of zero would indicate that the user was capable of positioning the object with high accuracy.

$$P_a = (x_a, y_a, z_a)$$

$$P_t = (x_t, y_t, z_t) \tag{5.1}$$

$$E_t = \sqrt{(x_a - x_t)^2 + (y_a - y_t)^2 + (z_a - z_t)^2}$$

The final performance evaluation examines user hand stability in controlling the haptic device. A two-dimensional vector represents the path deviation along the constrained directions at a given interval. Figure 5.2 depicts an x-direction translation trial with deviations along the constrained directions for one interval measurement.

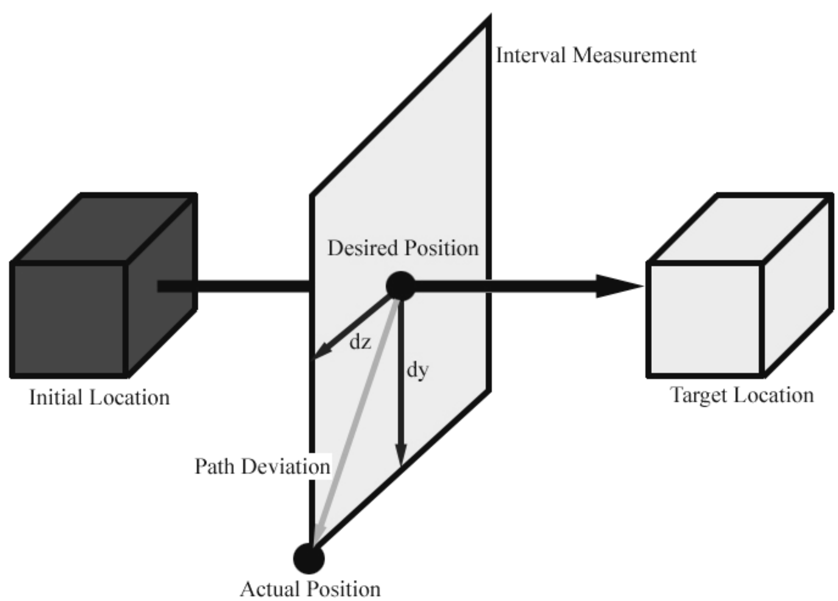

Figure 5.2. Path deviation interval measurement

The magnitude of the vector quantity yields a single measure of path deviation for a given interval. The total number of interval measurements is dependent on the time of completion.

The following calculation (equation 5.2) depicts the average path deviation, D_x, experienced during an x-translation along the y-direction (d_y) and z-direction (d_z) in n total intervals.

$$D_x = \frac{\sum_{i=1}^{n} \sqrt{(dy_i)^2 + (dz_i)^2}}{n} \tag{5.2}$$

5.5 Data Analysis

The user study resulted in 480 (40 participants and 12 trials) data values for each performance evaluation outlined in section 5.4. For each of three criteria (completion time, target error and average path deviation), an ANOVA procedure is evaluated to identify the statistical significance of the variation sources including sensory modality, translational direction and hand usage. An *Effect Tests* table was included to proportion the *Model* source of variation by the experimental factors. The statistical significance of each factor was determined by comparing the related probability value against the study's significance level.

5.5.1 Completion Time

Table 5.3 reflects the mean completion times for the non-haptics positioning trials. Users completed these trials in an average time of 17.182 $\pm$ 6.674 seconds. Table 5.4 contrasts mean completion times for trials that included the rendering of resistive and contact forces. Subjects completed the haptics-assisted trials in a mean time of 17.490 $\pm$ 6.593 seconds.

Table 5.3. Table for mean times in non-haptics trials

Non-Haptics	Dominant	Non-Dominant	Direction Avg.
X-direction	16.383	16.215	16.299
Y-direction	16.731	16.581	16.656
Z-direction	17.682	19.502	18.592
Hand Avg.	16.932	17.433	17.182

Table 5.4. Table for mean times in haptics trials

Haptics	Dominant	Non-Dominant	Direction Avg.
X-direction	18.424	16.953	17.689
Y-direction	18.552	17.222	17.887
Z-direction	15.741	18.050	16.896
Hand Avg.	17.572	17.409	17.490

Figure 5.3 illustrates median completion times of 16.281 seconds for the haptics-enabled trials and 15.703 seconds for trials using only visual perception. The variance of measurements for the two data series were also similar; 43.467 and 44.542 for haptic and non-haptics trials respectively. A comparison of mean values based on sensory modality did not indicate observable differences in completion times.

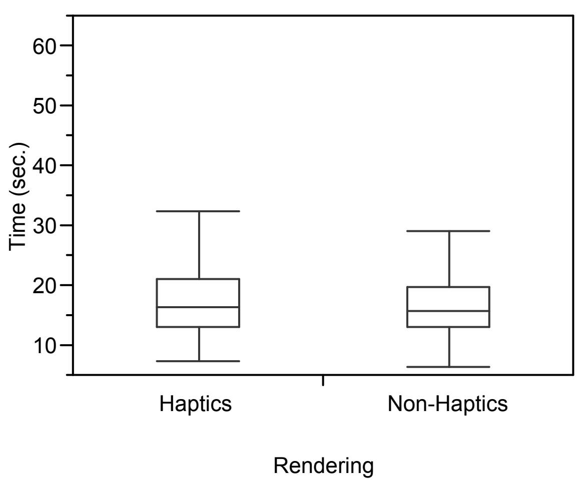

Figure 5.3. Box plot comparison of times based on sensory method

The second set of mean tables evaluates completion times along each of the coordinate directions. Table 5.5, 5.6 and 5.7 show that subjects required an average of 16.994 $\pm$ 7.078, 17.271 $\pm$ 6.396, and 17.744 $\pm$ 6.408 seconds to complete the task for positioning the object along the x-direction, y-direction and z-direction respectively.

Table 5.5. Table for mean times in x-direction trials

X-Direction	Dominant	Non-Dominant	Rend. Avg.
Haptics	18.424	16.953	17.689
Non-Haptics	16.383	16.215	16.299
Hand Avg.	17.403	16.584	16.994

Table 5.6. Table for mean times in y-direction trials

Y-Direction	Dominant	Non-Dominant	Rend. Avg.
Haptics	18.552	17.222	17.887
Non-Haptics	16.731	16.581	16.656
Hand Avg.	17.641	16.901	17.271

Table 5.7. Table for mean times in z-direction trials

Z-Direction	Dominant	Non-Dominant	Rend. Avg.
Haptics	15.741	18.050	16.896
Non-Haptics	17.682	19.502	18.592
Hand Avg.	16.711	18.776	17.744

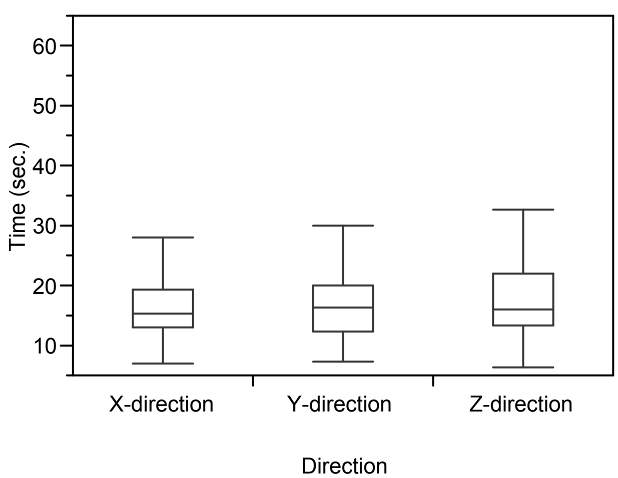

Figure 5.4. Box plot comparison of times based on direction

The box plot in Figure 5.4 shows the median values of 15.406, 16.195, and 16.135 for x-, y-, and z-directions and further reveals discrepancies in task completion times. It appears that translational direction possesses some effects on users' competition time. More specifically, positioning along a z-translation demanded the longest time, followed by y-direction and x-direction.

The last two mean tables evaluated time measurements based on hand control. Table 5.8 and 5.9 shows that the mean completion times with the dominant hand and non-dominant hand are 17.252 $\pm$ 6.662 and 17.421 $\pm$ 6.607 seconds respectively. Figure 5.5 portrays similar distributions of data values for each level of hand variation. Hence, the use of dominant or non-dominant hand did not appear to affect performance times during the part positioning experiment.

Table 5.8. Table for mean times in dominant hand trials

Dominant	Haptics	Non-Haptics	Direction Avg.
X-direction	18.424	16.383	17.403
Y-direction	18.552	16.731	17.641
Z-direction	15.741	17.682	16.711
Rend. Avg.	17.572	16.932	17.252

Table 5.9. Table for mean times in non-dominant hand trials

Non-Dominant	Haptics	Non-Haptics	Direction Avg.
X-direction	16.953	16.215	16.584
Y-direction	17.222	16.581	16.901
Z-direction	18.050	19.502	18.776
Rend. Avg.	17.409	17.433	17.421

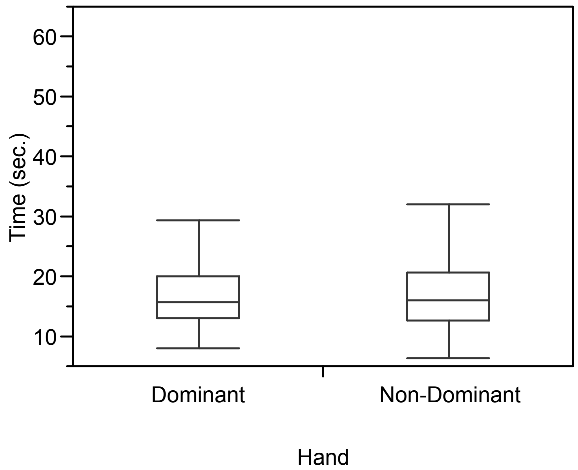

Figure 5.5. Box plot comparison of times based on hand usage

The final phase of data analysis for completion times during the part positioning experiment involved performing an ANOVA procedure. Tables 5.10 and 5.11 report the computed statistics for evaluating the significance of the sources of variation.

Table 5.10. ANOVA for time measurements

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	50	8563.854	171.277	5.8858
Error	429	12483.972	29.100	Prob > F
C. Total	479	21047.826		<.0001

Table 5.11. Effect tests for time measurements

Source	DF	Sum of Squares	F Ratio	Prob > F
Subject	39	8012.2283	7.0598	<.0001
Direction	2	201.6276	3.4644	0.0322
Hand	1	43.2463	1.4861	0.2235
Rendering	1	83.3379	2.8638	0.0913
Direction*Hand	2	183.7280	3.1568	0.0436
Direction*Rendering	2	200.4698	3.4445	0.0328
Hand*Rendering	1	16.9780	0.5834	0.4454
Direction*Hand*Rendering	2	20.0649	0.3448	0.7086

The variations in sensory modality did not reveal significant differences in mean completion times due to an *F-ratio* of 2.8638 and a *p-value* of 0.0913. This infers that the rendering of resistive and contact forces did not reduce performance times during the part positioning experiment. Variations in dominant and non-dominant hand control on completion times was also determined to be statistically insignificant (*F-ratio* = 1.4861, *p-value* = 0.2235).

The ANOVA procedure confirmed that variations in translational direction had a significant effect on task completion times (*F-ratio* = 3.4644, *p-value* = 0.0322). This concludes that the mean completion time for positioning along one of coordinate directions were statistically different from the other mean values for the other directions.

The combination of direction with sensory rendering factors (*F-ratio* = 3.4445, *p-value* = 0.0328) had a significant effect on completion times. This indicates that time measurements were dependent on the particular direction of translation and the sensory method used. The combined effects of direction with hand control was also determined to have significant influences on completion times (*F-ratio* = 3.1568, *p-value* = 0.0436). The probability value indicates that performance times varied between the different combinations of translational direction and hand usage.

5.5.2 Placement Accuracy

Table 5.12 summarizes the observed target error measurements for trials that provided haptic rendering of contact forces. During the haptics-enabled trials, subjects demonstrated a mean target error of 0.0388 $\pm$ 0.0438 ft.

Table 5.12. Table for mean target errors in haptics trials

Haptics	Dominant	Non-Dominant	Direction Avg.
X-direction	0.0218	0.0343	0.0281
Y-direction	0.0349	0.0323	0.0336
Z-direction	0.0544	0.0552	0.0548
Hand Avg.	0.0371	0.0406	0.0388

Table 5.13 contrasts the mean target error for trials in which users positioned the virtual object based on visual approximation. In the absence of force rendering, participants committed a mean target error of 0.3555 $\pm$ 0.5656 ft.

Table 5.13. Table for mean target errors in non-haptics trials

Non-Haptics	Dominant	Non-Dominant	Direction Avg.
X-direction	0.1922	0.3295	0.2609
Y-direction	0.1644	0.2035	0.1840
Z-direction	0.4925	0.7511	0.6218
Hand Avg.	0.2830	0.4280	0.3555

Participants were less accurate in placing the object at the target location using only visual cues. This was evident when considering that the mean target error of the non-haptics trials was nearly ten times larger than the mean value from the force rendered trials. The target error data set from the non-haptics trials featured a larger variation in measurements (0.3199) than data from the haptics-based trials (0.0019). The median target error for trials that featured haptics interaction was 0.0279 ft. while the non-haptics methods resulted in a value of 0.1548 ft.

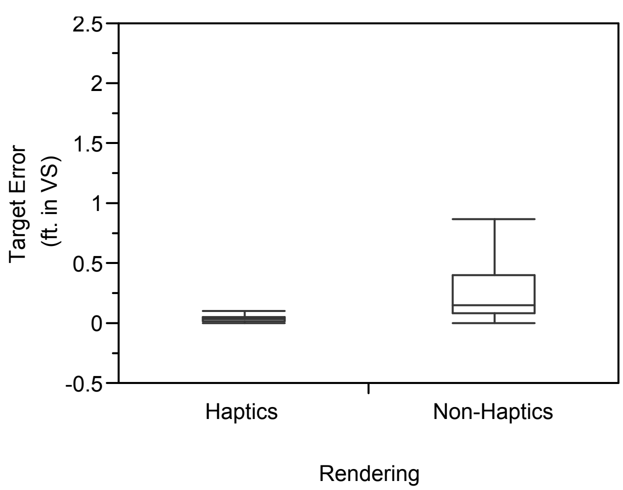

Figure 5.6. Box plot comparison of target errors based on sensory method

Figure 5.6 illustrates the distribution of measurements for each sensory method. The rendering of contact forces appeared to have assisted users in positioning components at targeted locations within the virtual environment.

The second series of mean tables report target error measurements based on translational direction. Table 5.14 summarizes the placement accuracy for trials along the x-direction. In completing these four trials, users produced a mean target error of 0.1445 $\pm$ 0.4732 ft. Table 5.15 outlines the mean target error measurements for positioning along the y-direction. Participants committed an average of 0.1088 $\pm$ 0.1665 ft. of target error during the y-direction trials. Table 5.16 compares the mean target error values of the four z-direction trials. Subjects demonstrated their placement accuracy with a mean target error of 0.3383 $\pm$ 0.5264 ft.

Table 5.14. Table for mean target errors in x-direction trials

X-Direction	Dominant	Non-Dominant	Rend. Avg.
Haptics	0.0218	0.0343	0.0281
Non-Haptics	0.1922	0.3295	0.2609
Hand Avg.	0.1070	0.1819	0.1445

Table 5.15. Table for mean target errors in y-direction trials

Y-Direction	Dominant	Non-Dominant	Rend. Avg.
Haptics	0.0349	0.0323	0.0336
Non-Haptics	0.1644	0.2035	0.1840
Hand Avg.	0.0997	0.1179	0.1088

Table 5.16. Table for mean target errors in z-direction trials

Z-Direction	Dominant	Non-Dominant	Rend. Avg.
Haptics	0.0544	0.0552	0.0548
Non-Haptics	0.4925	0.7511	0.6218
Hand Avg.	0.2734	0.4032	0.3383

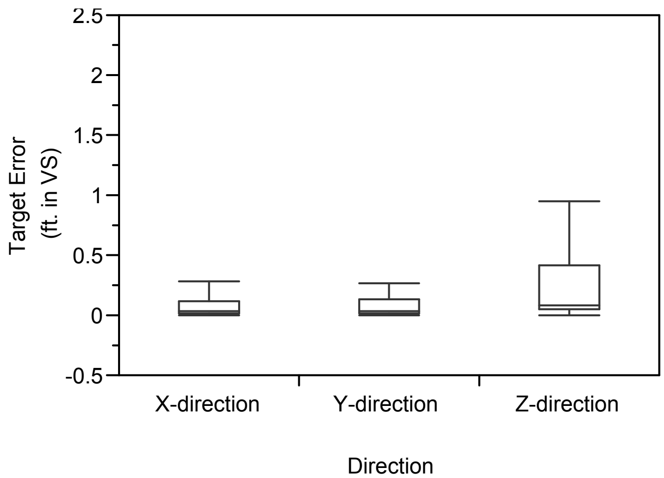

Figure 5.7. Box plot comparison of target errors based on direction

Figure 5.7 contrasts the distribution for each direction's measurements. The sample population had the greatest difficulty in placing the virtual component at the final location when translating along the z-direction. Positioning trials along the y-direction yielded the lowest mean of target error. The variations in measurements were also unique for the three trials. Data values resulting from the z-direction trials indicated higher variance (0.2771) than the x-direction (0.2239) and y-direction (0.0277). Target error measurements along the x- and y-directions conveyed similar median values; 0.0408 and 0.0381 ft., respectively. Data obtained from the z-direction trials indicated a median value of 0.0887 ft. The three mean tables and graphical comparison convey a distinction in placement accuracy based on translational direction.

The last consideration for target error performance examines variations in hand control. Table 5.17 contrasts the mean target error for trials that featured dominant hand guidance. When using their dominant hand, subjects performed a mean target error of 0.1600 ± 0.2561 ft.

Table 5.17. Table for mean target errors in dominant hand trials

Dominant	Haptics	Non-Haptics	Direction Avg.
X-direction	0.0218	0.1922	0.1070
Y-direction	0.0349	0.1644	0.0997
Z-direction	0.0544	0.4925	0.2734
Rend. Avg.	0.0371	0.2830	0.1600

Table 5.18. Table for mean target errors in non-dominant hand trials

Non-Dominant	Haptics	Non-Haptics	Direction Avg.
X-direction	0.0343	0.3295	0.1819
Y-direction	0.0323	0.2035	0.1179
Z-direction	0.0552	0.7511	0.4032
Rend. Avg.	0.0406	0.4280	0.2343

Table 5.18 summarizes target error measurements for the four trials involving non-dominant hand use. Participants produced a mean target error of 0.2343 $\pm$ 0.5512 ft. within the virtual environment when using their non-dominant hand.

The mean values of target error indicate higher placement accuracy when users positioned the object with their dominant hand. However, each data series contained similar median values with 0.0618 ft. for dominant and 0.0616 ft. for non-dominant (Figure 5.8). The variance of measurements for the non-dominant hand approach (0.3038) was larger than the dominant hand trials (0.0656). These variations in hand performances reflect different levels of dexterity between subjects. The effects of variations in hand control appeared significant on target error measurements during the part positioning experiment.

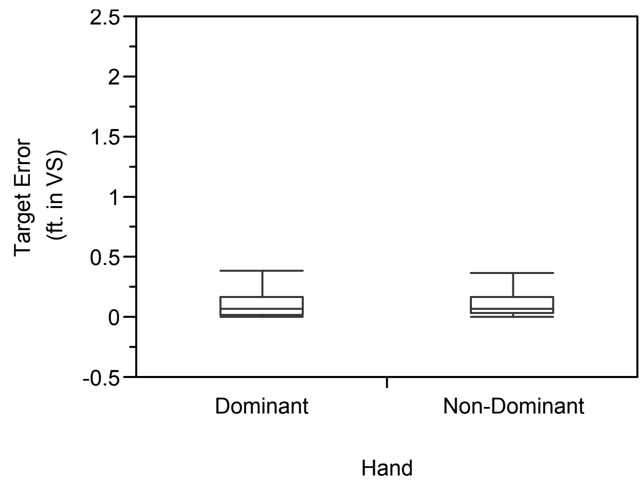

Figure 5.8. Box plot comparison of target errors based on hand usage

The summary of target error measurements based on experimental factors uncovered differences in variance. Comparing target error values based on sensory rendering demonstrated contrasting standard deviations; an observation confirmed in Figure 5.6. Furthermore, each translational direction had different standard deviations within their respective data series.

In order to perform statistical analysis using an *ANOVA* procedure, the variance of data for each level of an experimental factor must be similar. One solution is to apply a logarithmic transformation function (Ott and Longnecker 2001) since the coefficient of variation is approximately constant between factor levels. For sensory modality, the coefficient of variation for haptic (1.129) and non-haptic methods (1.591) were nearly equal. In terms of translational direction, the coefficient of variation for the y-direction (1.531) and z-direction (1.555) was approximately constant but was different from the x-direction (3.275). The coefficient of variation for the dominant hand (1.600) was less than the value (2.352) computed for the non-dominant hand effect.

The computed data series of logarithm values for target error, *log(T_E)*, demonstrated similar variances between levels within the three experimental factors. The standard deviations for haptics (1.2125) and non-haptics (1.3572) were more similar than the values associated with the original data series. The new data series demonstrated standard deviations of 1.7800, 1.3596, and 1.35563 for x-, y-, and z-directions, respectively. The transformed target error values reflected standard deviations of 1.6785 and 1.5491 for dominant and non-dominant hand use.

Using the transformed data series, an *ANOVA* procedure evaluated the statistical significance of the sources of variation in the experiment on placement accuracy. Tables 5.19 and 5.20 report the statistics concerning the logarithmic values of target error.

Table 5.19. ANOVA for logarithm of target error measurements

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	50	755.1676	15.1034	12.9840
Error	429	499.0257	1.1632	Prob > F
C. Total	479	1254.1932		<.0001

Table 5.20. Effect tests for logarithm of target error measurements

Source	DF	Sum of Squares	F Ratio	Prob > F
Subject	39	96.09790	2.1183	0.0002
Direction	2	76.70617	32.9712	<.0001
Hand	1	22.44577	19.2961	<.0001
Rendering	1	144.01886	123.8094	<.0001
Direction*Hand	2	13.77160	5.9196	0.0029
Direction*Rendering	2	11.37532	4.8895	0.0079
Hand*Rendering	1	9.47850	8.1484	0.0045
Direction*Hand*Rendering	2	7.16325	3.0790	0.0470

The *ANOVA* procedure indicated that all experimental factors were statistically significant. As an individual effect, the haptic rendering of contact forces assisted users in positioning objects at target locations within the virtual environment (*F-ratio* = 123.8094, *p*-

value < 0.0001). Variations in translational direction had a significant influence on placement accuracy based on an *F-ratio* of 32.9712 and a *p-value* of less than 0.0001. In addition, the use of dominant or non-dominant hand affected placement accuracy measurements in the experiment (*F-ratio* = 19.2961, *p-value* < 0.0001).

The sources of variation featuring combined effects were all significant. These statistics indicate that the users' ability to position objects within a virtual environment is dependent on which hand is performing the displacement, the direction of travel, and the sensory method used. Subjects were least accurate when positioning along the z-direction using the non-dominant and only visual cues. The greatest demonstration of placement accuracy would occur in a task along the y-direction using the dominant hand and haptic assistance.

5.5.3 Path Deviation

The first two mean tables examine path deviation measurements in terms of sensory modality. Table 5.21 summarizes the mean path deviation for trials that rendered resistive forces to ensure steady object displacements in the virtual environment. Subjects committed a mean path deviation of 0.9821 $\pm$ 0.5856 ft. during these six trials.

Table 5.21. Table for mean path deviation in haptics trials

Haptics	Dominant	Non-Dominant	Direction Avg.
X-direction	1.1699	1.0418	1.1058
Y-direction	0.8424	0.9189	0.8807
Z-direction	0.9575	0.9623	0.9599
Hand Avg.	0.9899	0.9743	0.9821

Table 5.22. Table for mean path deviation in non-haptics trials

Non-Haptics	Dominant	Non-Dominant	Direction Avg.
X-direction	3.3055	3.1407	3.2231
Y-direction	2.1779	2.1390	2.1585
Z-direction	3.4514	3.7021	3.5767
Hand Avg.	2.9783	2.9939	2.9861

Table 5.22 outlines the mean path deviation values for non-haptics trials. The sample population produced a mean value of 2.9861 $\pm$ 2.2625 ft. for path deviation when using only visual perception.

The two sensory methods revealed contrasts in path deviation measurements. The overall mean value associated with the non-haptics trials was over three times larger than the value obtained from the haptics-based trials. In addition, the median value for haptic trials (0.8685 ft) was less than the non-haptics (2.3284 ft.). The haptics and non-haptics measurements revealed different variances in data; 0.3429 and 5.1192, respectively. Figure 5.9 illustrates the distributions of the original series based on sensory modality. The use of haptic and non-haptic approaches appeared to have influenced path deviation measurements during the positioning experiment.

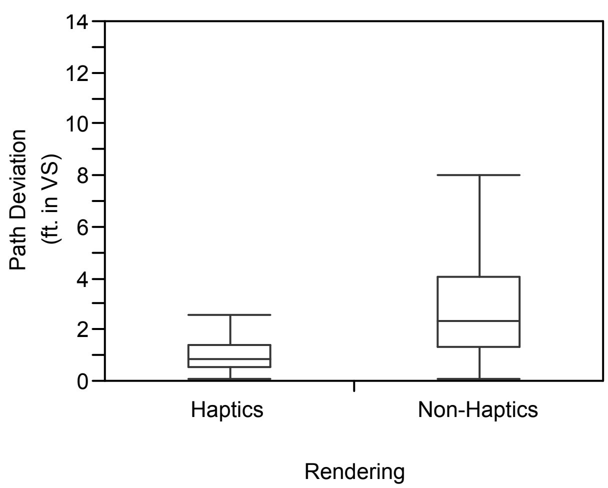

Figure 5.9. Box plot comparison of path deviation based on sensory method

Table 5.23. Table for mean path deviation in y-direction trials

X-Direction	Dominant	Non-Dominant	Rend. Avg.
Haptics	1.1699	1.0418	1.1058
Non-Haptics	3.3055	3.1407	3.2231
Hand Avg.	2.2377	2.0912	2.1645

Table 5.23 contrasts the steadiest of user motions along the x-direction. The sample population yielded a mean path deviation of 2.1645 $\pm$ 1.7957 ft. in completing the four x-direction trials.

Table 5.24. Table for mean path deviation in y-direction trials

Y-Direction	Dominant	Non-Dominant	Rend. Avg.
Haptics	0.8424	0.9189	0.8807
Non-Haptics	2.1779	2.1390	2.1585
Hand Avg.	1.5101	1.5290	1.5196

Table 5.24 summarizes path deviation measurements for trials along the y-direction. The mean value of path deviation for the four y-direction translations equaled 1.5196 $\pm$ 1.4880 ft.

Table 5.25. Table for mean path deviation in z-direction trials

Z-Direction	Dominant	Non-Dominant	Rend. Avg.
Haptics	0.9575	0.9623	0.9599
Non-Haptics	3.4514	3.7021	3.5767
Hand Avg.	2.2045	2.3322	2.2683

Table 5.25 outlines the mean path deviation of participants in translating along the z-direction. The sample population performed the four z-direction trials with a mean path deviation of 2.2683 $\pm$ 2.3390 ft. within the virtual simulation.

Figure 5.10 contrasts the distribution of the original path deviation measurements along each direction. The diagram depicts similarities in distribution for the x- and z-directions. Users performed the y-translations with more controlled hand input than the other directions. Based on standard deviations, participants completed the y-direction translations with less variation between measurements. Comparing the three directions based on median values revealed similar trends with the lowest occurring within the y-direction series. From the three mean tables and the graphical comparison, the variation in direction appeared to have affected the amount of path deviation committed during the part positioning experiment.

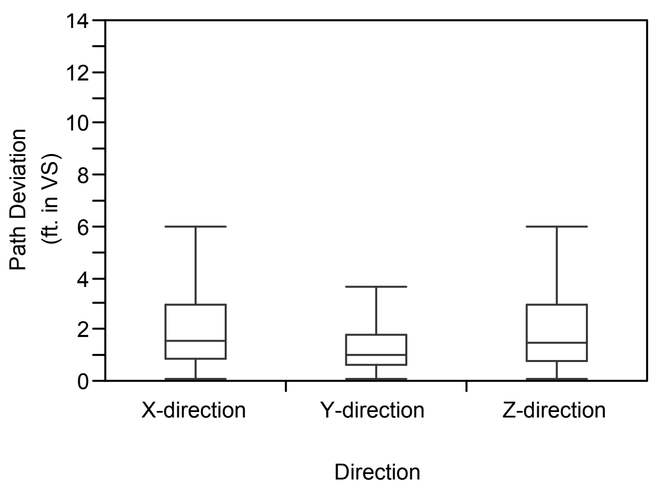

Figure 5.10. Box plot comparison of path deviation based on direction

Table 5.26. Table for mean path deviation in dominant hand trials

Dominant	Haptics	Non-Haptics	Direction Avg.
X-direction	1.1699	3.3055	2.2377
Y-direction	0.8424	2.1779	1.5101
Z-direction	0.9575	3.4514	2.2045
Rend. Avg.	0.9899	2.9783	1.9841

The final consideration in evaluating user path deviation focused on hand usage. Table 5.26 reports the mean values for procedures that involved dominant hand control for teleoperation. The sample population committed a mean path deviation of 1.9841 $\pm$ 1.9160 ft. during these trials.

Table 5.27. Table for mean path deviation in non-dominant hand trials

Non-Dominant	Haptics	Non-Haptics	Direction Avg.
X-direction	1.0418	3.1407	2.0912
Y-direction	0.9189	2.1390	1.5290
Z-direction	0.9623	3.7021	2.3322
Rend. Avg.	0.9743	2.9939	1.9841

Table 5.27 examines path deviation values for trials that featured non-dominant hand guidance of the virtual component. The overall mean for the six trials was equivalent to 1.9841 $\pm$ 1.9512 ft.

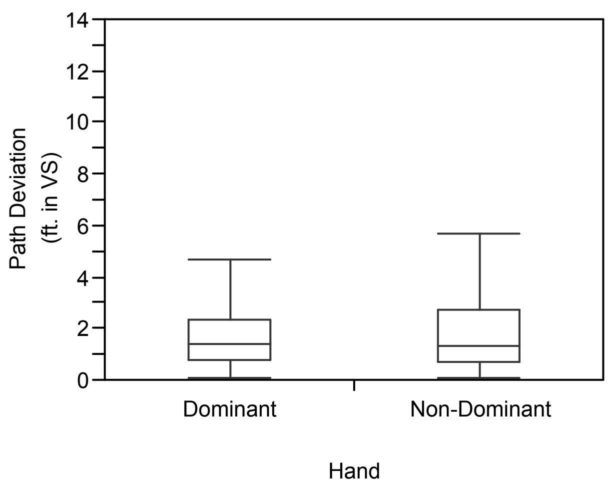

Figure 5.11. Box plot comparison of path deviation based on hand usage

Figure 5.11 demonstrates the distribution of measurements for each hand. A comparison of path deviation values in terms of hand usage indicates minimal discrepancies in performances. Both data series have similar mean values for path deviation. The median value for non-dominant hand performance (1.2978 ft.) was less than the value for the dominant hand trials (1.4091 ft.). The variation in measurements for the non-dominant hand trials was slightly greater than the dominant hand performance; 3.8073 and 3.6711, respectively. Variations in hand usage did not appear to have influence the path deviation measurements.

Similar to the target error evaluation, measurements between each level of the experimental factors exhibited different variances in data. A logarithmic transformation function was used since the coefficient of variation between factor levels was approximately constant. For sensory rendering, measurements from the haptics trials exhibited a coefficient of 0.5962 while the value for non-haptics trials was 0.7576. The coefficients were similar between dominant (0.9656) and non-dominant (0.9834) variations. In terms of direction, the three coefficients were relatively similar for x-direction (0.8296), y-direction (0.9792), and z-direction (1.0311).

Applying the transform function on the original data series resulted in similar standard deviations between the levels of each factor. The transformed series featured standard deviations of 0.6766 and 0.8360 for haptic and non-haptics methods, respectively. The standard deviation of measurements based on active hand demonstrated values of 0.8942 for dominant and 0.9359 for non-dominant hand. Standard deviation values for x-direction (0.8435), y-direction (0.8722), and z-directions (0.9791) were relatively similar.

An ANOVA procedure for the transformed data series computed the statistical significance of the sources of variation in the experiment on path deviation. Tables 5.28 and 5.29 report the results of the statistical analysis.

Table 5.28. ANOVA for logarithm of path deviation measurements

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	50	178.20124	3.56402	6.8882
Error	429	221.96939	0.51741	Prob > F
C. Total	479	400.17063		<.0001

Table 5.29. Effect tests for logarithm of path deviation measurements

Source	DF	Sum of Squares	F Ratio	Prob > F
Subject	39	34.132970	1.6915	0.0071
Direction	2	1.557967	1.5055	0.2231
Hand	1	0.120241	0.2324	0.6300
Rendering	1	19.912896	38.4856	<.0001
Direction*Hand	2	0.044197	0.0427	0.9582
Direction*Rendering	2	3.937160	3.8047	0.0230
Hand*Rendering	1	0.023687	0.0458	0.8307
Direction*Hand*Rendering	2	0.068854	0.0665	0.9356

The variation in rendering methods was determined to have a significant influence on the measured responses (*F-ratio* = 38.4856, *p-value* < 0.0001). The haptic rendering of resistive forces allowed participants to position the virtual object along a specified trajectory with less deviation than methods using only visual modality.

From an *F-ratio* of 0.2324 and a *p-value* of 0.6300, the test concluded that subjects guided the virtual component with similar stability for each hand. This demonstrates the usability of haptic devices in performing translation tasks regardless of hand control. The analysis of variance procedure did not detect significant discrepancies in path deviation measurements due to variations in translational direction (*F-ratio* = 1.5055, *p-value* = 0.2231). This infers that subjects committed similar amounts of path deviation along the three coordinate directions.

The combined effect of translational direction and sensory perception was statistically significant on the amount of path deviation committed during the part positioning experiment (*F-ratio* = 3.8047, *p-value* = 0.0230). This indicates that the steadiest of users in displacing an object along a specific trajectory was dependent on the direction of travel and the provided sensory rendering. The analysis did not report additional significant sources of variation from combined effects.

5.5.4 User Preference

After completing the twelve trials, participants answered three questions relevant to the part positioning experiment. The first question asked participants to specify which translational direction was the most difficult during the non-haptics positioning trials. The second question presented a similar inquiry but concerned trials featuring haptic feedback. Figure 5.12 contrasts the sample population's response for the two questions.

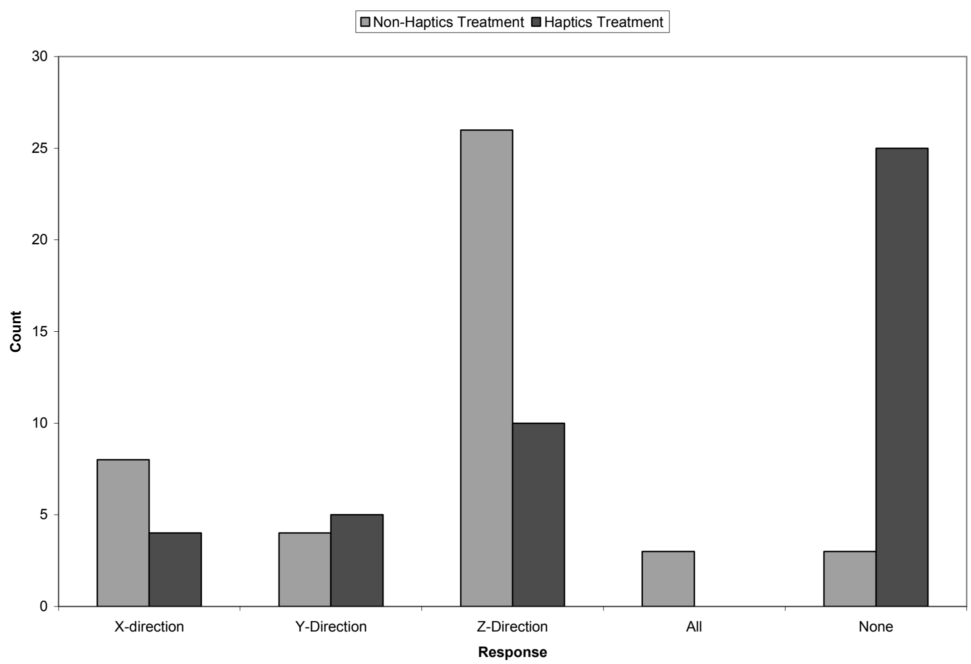

Figure 5.12. Task direction difficulty base for haptic and non-haptic treatments

When provided only visual information, 59.0% of the participants regarded the z-direction trials as being the most difficult. Only 22.7% of the sample population considered the same direction difficult when provided haptic assistance. Three individuals reported difficulty in positioning the virtual component along all of the directions when using visual perception. In contrast, 56.8% of the subjects found none of the directions difficult when trials featured haptic feedback.

The final question asked participants to assess the usefulness of force rendering during the part positioning experiment. From the sample population, 72.7% of subjects regarded haptics interaction as *Very Useful* for completing the trials. An additional 25.0% valued force feedback as being *Useful*, while only 2.2% were neutral in their response. None of the subjects regarded haptics as *Useless*. Figure 5.13 depicts the perceived usefulness of haptic feedback in completing the part positioning experiment. The responses provided on the post-study questionnaire reveal favorable preference for force feedback implementation in performing positioning tasks within a virtual assembly simulation.

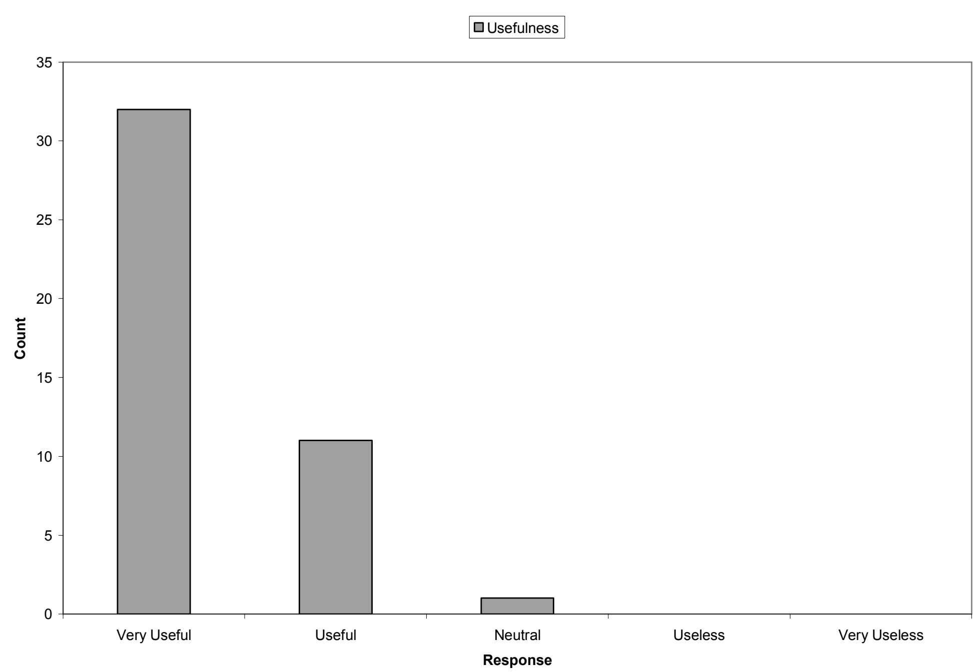

Figure 5.13. Force feedback usefulness in part positioning experiment

5.6 Conclusion

The objective of the experiment was to evaluate the performance effects of haptic interaction when positioning objects in a virtual simulation. Section 5.2 outlined several hypotheses concerning the use of haptic modality in terms of completion time, placement accuracy, and path deviation.

Statistical analysis concluded that haptic rendering did not reduce completion times during the experiment (*F-ratio* = 2.8638, *p-value* = 0.0913). One explanation includes the fact that users experienced haptic rendering that could have impeded their hand motion. Furthermore, the majority (70.4%) of users indicated that they did not have previous exposure to haptic devices. Force rendering presents a new experience to some individuals that could have affected their performance times.

The statistical evaluation determined that haptic interaction improved placement accuracy during the part positioning experiment (*F-ratio* = 123.8094, *p-value* < 0.0001). In the haptics-assisted trials, rendered contact forces enabled participants to place virtual components at target locations with less error than trials requiring visual approximation. The haptic feedback notified participants of the correct placement of the virtual object.

The final measure of user performance, path deviation, also revealed improvements from haptic feedback (*F-ratio* = 38.4856, *p-value* < 0.0001). Subjects were capable of guiding a virtual object along a target trajectory more steadily when provided resistive haptic cues than tasks using visual perception.

Statistical analysis addressed the hypothesis concerning the use of three translational directions. The variation in directions had a significant effect on completion times (*F-ratio* = 3.4644, *p-value* = 0.0322) and placement accuracy (*F-ratio* = 32.9712, *p-value* < 0.0001).

However, the statistical analysis determined that variations in direction did not influence the amount of path deviation committed during the positioning trials (*F-ratio* = 1.5055, *p-value* = 0.2231).

The analysis also addressed the research hypothesis concerning active hand. Statistical evaluation concluded that variations in dominant and non-dominant hand use was not significant on completion times (*F-ratio* = 1.4861, *p-value* = 0.2235) and path deviation (*F-ratio* = 0.2324, *p-value* = 0.6300), but affected users' ability to position objects at target locations (*F-ratio* = 19.2961, *p-value* < 0.0001).

During the part positioning experiment, the combination of direction and sensory modality had significant influences on performance including completion time (*F-ratio* = 3.4445, *p-value* = 0.0328), target error (*F-ratio* = 4.8895, *p-value* = 0.0079), and path deviation (*F-ratio* = 3.8047, *p-value* = 0.0230). This indicates that a user's ability of positioning virtual objects within a virtual environment is dependent on the direction of travel and the assistance of haptic feedback.

CHAPTER 6. ASSEMBLY SIMULATION EXPERIMENT

6.1 Introduction

The manual assembly of components is a common activity in manufacturing. Boothroyd et al. (1994) categorize assembly scenarios into bench, multi-station, modular, custom, and flexible assemblies in terms of the accessibility of the components to the worker. Some components demand two hands due to weight, dimensions, or lack of grasping features. The handling of assembly components can account for almost 80% of the total assembly time (Molloy et al. 1998). In developing an assembly simulation, all aspects of real assembly procedures must be addressed adequately.

6.2 Hypotheses

The objective of the experiment is to evaluate the benefits of haptic interaction in performing manual assembly tasks within a virtual simulation. We hypothesize that the addition of force feedback will enable users to complete manual assembly sequences in less time than visuals-only procedures. With the assistance of haptic rendering, participants will minimize unnecessary hand motions that can potentially increase the total assembly times.

The second hypothesis is that the use of two hands will enable participants to complete assembly sequences in less time than one-hand performance. By using two hands, subjects will be able to manipulate multiple digital models simultaneously. In addition, the use of two-hands promotes beneficial interactions including stabilizing and fixing dynamic objects. The use of one hand will permit the direct manipulation of only one object at a time.

The third hypothesis of this experiment is that the addition of a static virtual fixture will allow users to complete assemblies in less time than sequences containing all dynamic components. The use of a fixture will allow participants to assemble components with less concern regarding their hand steadiness than operations involving the manipulation of dynamic objects.

6.3 Experimental Procedures

Given a set of virtual objects, subjects are required to complete a specific assembly task using the haptic devices. To perform the assembly, participants must establish mate and alignment conditions between virtual parts. In some of the trials, users are required to insert a bolt through a hole-based feature. Participants will complete eight trials based on three experimental factors including sensory modality, interaction method, and task complexity. The goal of the experiments is to identify the effect of each factor on the assembly result through statistic procedures.

6.3.1 Experimental Factors

To investigate the effect of sensory modality, the subjects are required to perform the same assembly with or without haptic force feedback. The second experimental factor features one and two-handed interactions. Participants are required to perform the task by using their dominant hand or both hands.

The final experimental factor concerns task difficulty. Two assembly scenarios simulated a series of actions encountered in real world tasks. The first assembly involved participants completing a five-piece puzzle depicted in Figure 6.1. This was the simple task for the following reasons. The red base object remained static throughout the entire performance and served as a fixture for the four dynamic components. Each virtual object had initial locations within a small workspace and required small three-dimensional input from the haptic device. To complete the assembly, users must mate and align surfaces for all five of puzzle pieces.

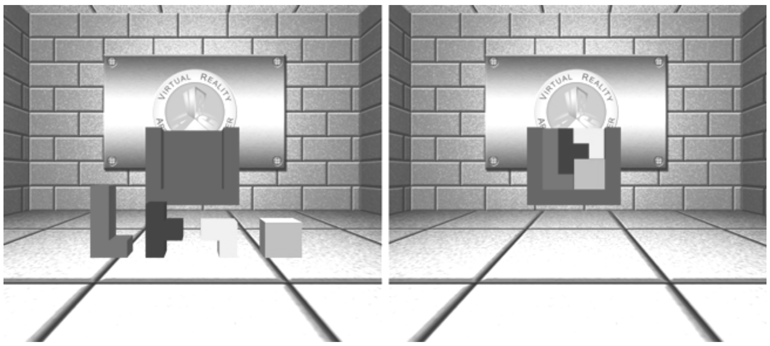

Figure 6.1. Simple assembly sequence

The second scenario presented to users was the complex assembly. Three dynamic virtual components were initially located at far distances within the virtual environment: a bolt, an eyelet, and a crossbar member. Selecting each object required large translational input in the haptic workspace. All objects were small and required fine hand movements to assemble properly. The sequence involved establishing mating conditions between surfaces of components and aligning hole-based features. These actions were the precursor to a bolt insertion. Figure 6.2 illustrates this assembly sequence.

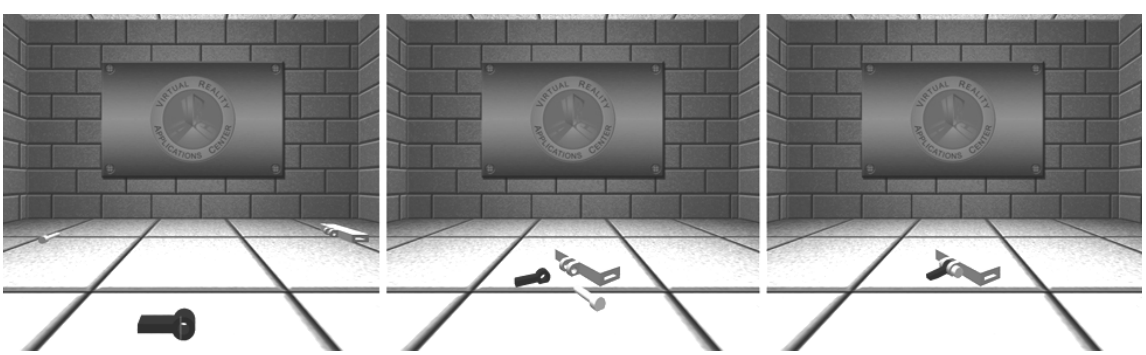

Figure 6.2. Complex Assembly Sequence

6.3.2 Experiment Structure

The experiment featured a randomized complete block design. Each participant completed eight trials in individually random sequences without replication. Table 6.1 lists all trials based on combinations of sensory rendering, interaction method, and task complexity. Subjects were informed of these factors prior to each trial.

Table 6.1. Assembly simulation experiment trials

Trial	Complexity	Interaction	Rendering
1	Simple	Single	Non-Haptics
2	Simple	Dual	Non-Haptics
3	Complex	Single	Non-Haptics
4	Complex	Dual	Non-Haptics
5	Simple	Single	Haptics
6	Simple	Dual	Haptics
7	Complex	Single	Haptics
8	Complex	Dual	Haptics

6.4 Performance Evaluation

The user performance in the experiment is assessed by the assembly completion time; recorded in seconds. A completed assembly assumed that each virtual component was in the correct location using the proper sequence of actions. Prior to each trial, users received the solution to the assembly since the intent of the experiment is to evaluate the subjects' performance and not their decision-making skills. Participants could use as much time as needed to complete each trial.

6.5 Data Analysis

The experiment produced 320 measurements for assembly time. The summary process used six mean tables to compare the data based on the three experimental factors.

The first two mean tables organize measurements based on haptic and non-haptic trials. The second set of two mean tables examines completion times by interaction methods. The last two tables contrast the mean performance times based on task complexity. Box plot diagrams were used to convey the distribution of measurements for each level of an experimental factor.

After the summary process, an ANOVA procedure is used to determine the statistical significance of each source of variation in the experiment. A comparison between the resulting probability values against the study's significance level assisted in concluding the analysis.

6.5.1 Completion Time

The first two mean tables examine the completion times based on sensory modality. Table 6.2 and 6.3 summarize the mean assembly times for the trials without and with haptic interaction respectively. It can be seen that subjects required an average time of 41.366 $\pm$ 27.970 seconds to complete each of the non-haptics assembly scenarios. However, with haptic rendering, they can complete the same task in a mean time of 39.062 $\pm$ 27.830 seconds.

Table 6.2. Table for mean times in non-haptics trials

Non-Haptics	Complex	Simple	Hand Avg.
Single	38.031	36.846	37.438
Dual	43.930	46.656	45.293
Task Avg.	40.981	41.751	41.366

Table 6.3. Table for mean times in haptics trials

Haptics	Complex	Simple	Hand Avg.
Single	35.003	41.913	38.458
Dual	37.093	42.241	39.667
Task Avg.	36.048	42.077	39.062

Figure 6.3 depicts the distribution of time measurements based on sensory methods. When using haptic interaction is used, the median complete time value dropped from 32.635 seconds to 29.020 seconds. It can be concluded that sensory modality has a minimal effect on completion times during the assembly experiment.

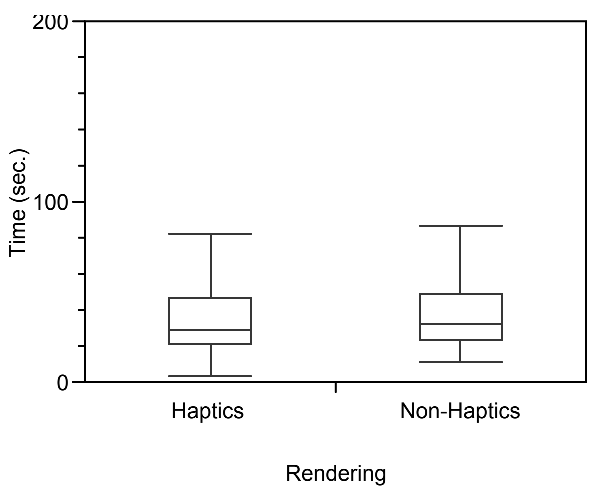

Figure 6.3. Box plot comparison of times based on rendering method

Table 6.4 and 6.5 summarizes time measurements for trials that required single-hand and two hands to complete the assembly sequences respectively. Users required a mean time of 37.948 $\pm$ 23.440 seconds and 42.480 $\pm$ 31.618 seconds to complete the assembly operations using one hand and two hands respectively.

Table 6.4. Table for mean times in single-handed trials

Single	Complex	Simple	Rend. Avg.
Haptics	35.003	41.913	38.458
Non-Haptics	38.031	36.846	37.438
Task Avg.	36.517	39.379	37.948

Table 6.5. Table for mean times in dual-handed trials

Dual	Complex	Simple	Rend. Avg.
Haptics	37.093	42.241	39.667
Non-Haptics	43.930	46.656	45.293
Task Avg.	40.511	44.448	42.480

Figure 6.4 contrasts the distribution of measurements based on interaction methods. The median values show subjects required more time when providing input using two hands (31.985 seconds) than using single hand (30.150 seconds). The high variance in measurement for the two-handed interaction (999.754) reflects the different level of dexterity between participants as opposed to using one hand (549.438). Variations in interaction methods did not appear to have affected completion times during the assembly simulation experiment.

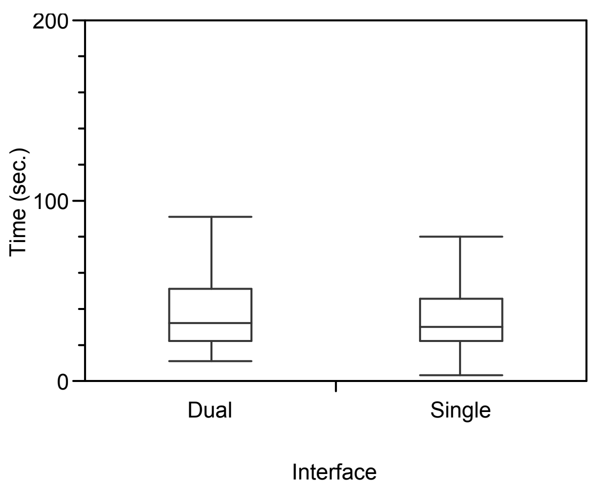

Figure 6.4. Box plot comparison of times based on interaction method

The final method of variation in the experiment concerned task difficulty. Table 6.6 and 6.7 outlines the mean completion times for trials that featured the simple and complex assembly task respectively. Figure 6.5 contrasts the completion times based on task difficulty. Participants completed the complex assembly task (38.514 ± 27.338) in less time than simple task (41.914 ± 28.395). Furthermore, the simple task exhibited greater variance (806.321) than the complex task (747.366). The simple task required additional time for correction if virtual objects lost their initial orientation. The variations in task complexity did not appear to affect completion times in the experiment since the observed differences were minimal.

Table 6.6. Table for mean times for simple assembly trials

Simple	Single	Dual	Rend. Avg.
Haptics	41.913	42.241	42.077
Non-Haptics	36.846	46.656	41.751
Hand Avg.	39.379	44.448	41.914

Table 6.7. Table for mean times for complex assembly trials

Complex	Single	Dual	Rend. Avg.
Haptics	35.003	37.093	36.048
Non-Haptics	38.031	43.930	40.981
Hand Avg.	36.517	40.511	38.514

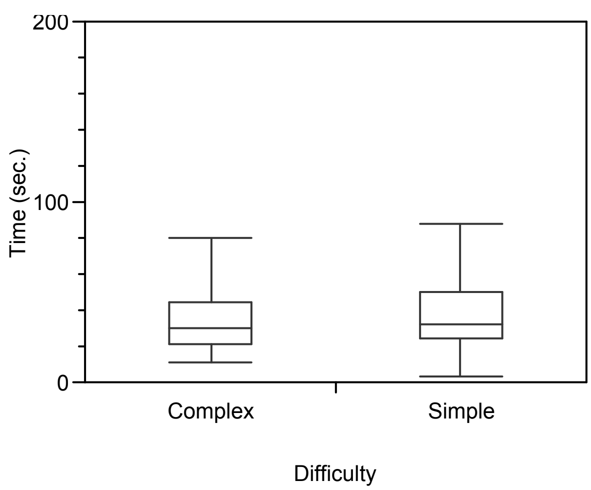

Figure 6.5. Box plot comparison of times based on task complexity

An *ANOVA* procedure analyzed the statistical significance of the sources of variation in the experiment. Using the corresponding probability values, inferences concerning each experimental factor was determined. Tables 6.8 and 6.9 summarize the results of the *ANOVA* and *Effect Tests*.

Table 6.8. ANOVA for time measurements

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	46	83803.87	1821.82	3.0297
Error	273	164161.35	601.32	Prob > F
C. Total	319	247965.22		<.0001

Table 6.9. Effect tests for time measurements

Source	DF	Sum of Squares	F Ratio	Prob > F
Subject	39	79191.267	3.3768	<.0001
Difficulty	1	530.141	0.8816	0.3486
Interface	1	87.362	0.1453	0.7034
Rendering	1	935.028	1.5549	0.2135
Difficulty*Interface	1	31.038	0.0516	0.8204
Difficulty*Rendering	1	58.697	0.0976	0.7550
Interface*Rendering	1	145.085	0.2413	0.6237
Difficulty*Interface*Rendering	1	160.915	0.2676	0.6054

From an *F-ratio* of 1.5549 and a *p-value* of 0.2135, variations in sensory modality did not affect completion times. Although the mean completion time for the haptics trials was less than the value for the non-haptics trials, further evaluation inferred that the observation was insignificant. The conclusion is that the haptic interaction did not reduce completion times for performing assembly operations within the virtual simulation.

Variations in interaction methods was determined to be statistically insignificant (*F-ratio* = 0.1453, *p-value* = 0.7034). The results of the statistical evaluation inferred that participants required similar amounts of time when completing assembly operations using either one or two hands.

The *ANOVA* procedure did not attribute significant influences to task complexity on completion times. Although participants assembled the complex scenario in less time than simple task, an *F-ratio* of 0.8816 and a *p-value* of 0.3486 regarded this observation not significant. The statistical analysis did not indicate any significant interactions between the experimental factors used during the study.

6.6.2 User Preference

After performing the trials within the assembly simulation experiment, participants answered four relevant questions on the post-study questionnaire. The intent of the first two questions was to determine the ease of performing the assembly tasks using non-haptic and haptic sensory methods. Figure 6.6 summarizes the responses provided by the sample population.

The majority of the sample population indicated a *Neutral* response for trials using only visual perception; 36.3%. Equal portions (29.5%) of the total users evaluated the same tasks as either *Easy* or *Difficult*. Only 4.5% of the sample population considered the non-haptics trials *Very Easy*. None of the participants considered the non-haptics trials to be *Very Difficult*.

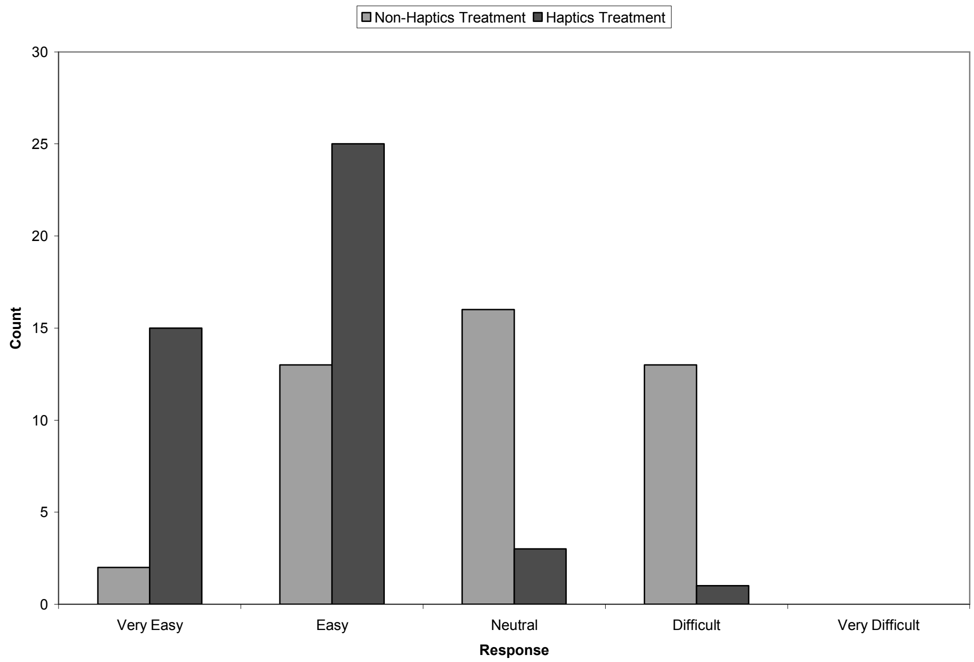

Figure 6.6. Ease the assembly tasks for haptic and non-haptic treatments

An overwhelming percentage of the participants regarded the force-assisted trials as either *Very Easy* (34.0%) or *Easy* (56.8%). An additional 6.8% of subjects were *Neutral* in their response. Only 2.2% of the sample population assessed the haptics-based trials as *Difficult*. No one in the sample population evaluated the haptics assembly trials as being *Very Difficult*.

The third question regarding the experiment required users to indicate the usefulness of force rendering in completing the assembly sequences. The majority of participants, 56.8%, regarded force feedback as *Useful*. An additional 43.1% of users found haptic feedback *Very Useful*. A small percentage (9.0) of users was *Neutral* in their response. Figure 6.7 outlines the responses from the sample population.

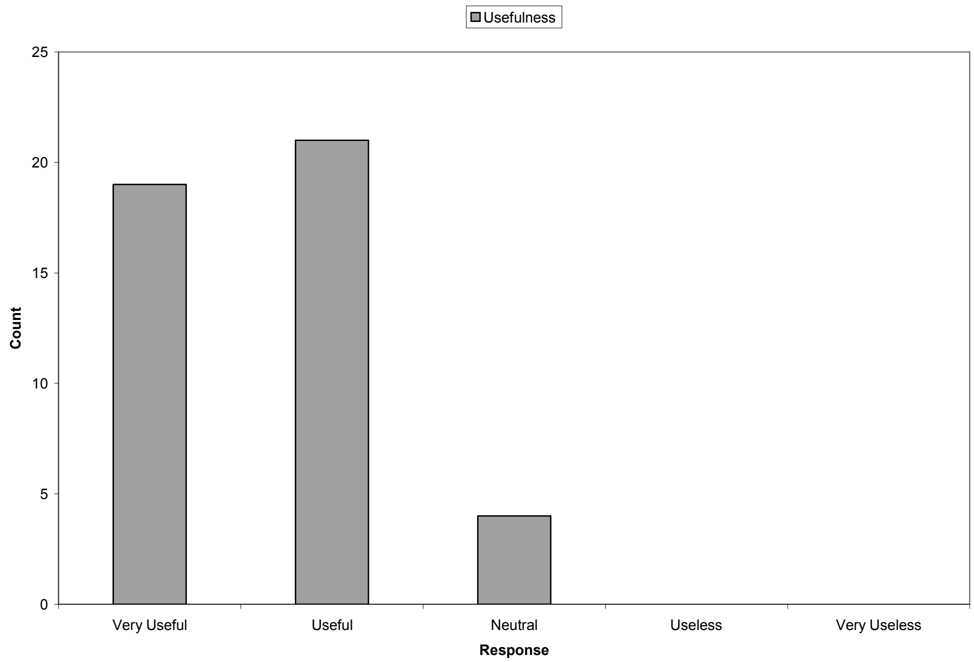

Figure 6.7. Force feedback usefulness in assembly simulation experiment

The final inquiry regarding the assembly simulation experiment focused on interaction techniques (Figure 6.8). This question was included to assess the sample population's preference of using multiple haptic devices to complete the assembly sequences. The largest percentage (77.2%) of users viewed two-handed interaction as a *Benefit*. Two of the participants noted that the ability of using two hands presented a realistic simulation of assembly processes. Four subjects expressed satisfaction in handling multiple objects simultaneously. One individual particularly found dual-handed interaction valuable for stabilizing a component with one hand while performing an action with the other.

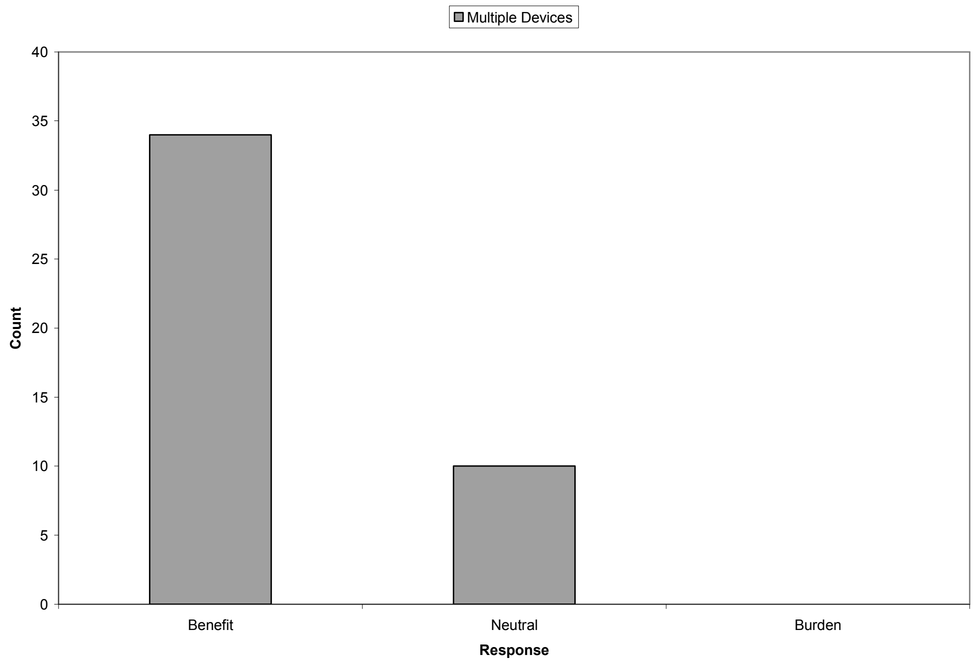

Figure 6.8. User rating of multiple device interaction

The remaining portion of the sample population was *Neutral* concerning the use of multiple devices. One participant noted an advantage and disadvantage for the interaction technique. They noted that the ability to manipulate two objects with each hand was beneficial, but controlling the same object with both hands presented a unique challenge. Another subject thought it was much easier to use one device instead of concentrating on two. None of the participants assessed multiple device interaction as a *Burden*.

6.6 Conclusion

The intent of the experiment was to evaluate the performance effect of haptic interaction on completing manual assembly tasks in a VR simulation. The first hypothesis anticipates that the addition of haptic feedback would allow users to complete assembly sequences in less time than using only visual perception. Statistical analysis using an

ANOVA procedure concluded that variations in sensory modality had an insignificant effect on performance times (*F-ratio* = 1.5549, *p-value* = 0.2135).

The second hypothesis considered user performance in terms of interaction methods. Subjects required less time to complete assembly tasks when using one hand instead of two. However, the statistical analysis inferred that there were no significant differences between the single and dual-handed interaction methods (*F-ratio* = 0.1453, *p-value* = 0.7034). One important observation from the study was the different methods of two-handed interaction. A small portion of subjects would perform the tasks predominantly with one hand while the second hand stabilized or adjusted other components within the assembly. The majority of the participants utilized both hands actively throughout the entire simulation.

The last statistical analysis examined completion times based on task complexity. Users were capable of completing the complex task in less time than the simple assembly sequence. The *ANOVA* procedure concluded that this observation was inconclusive (*F-ratio* = 0.8816, *p-value* = 0.3486). One observed external source of variation concerned the correction of part orientation. Some of the participants would take the selected component and collide it with other parts in the scene causing those objects to lose orientation or position. For each affected object, additional time was required to rearrange the component into a suitable transformation.

CHAPTER 7. CONCLUSION AND FUTURE WORK

7.1 Conclusion

The objective of this research was to investigate the effects of haptics-based interaction in performing virtual assembly. The research involved an extensive study where users performed similar assembly tasks in two treatments: visuals-only and visuals with haptics. The research identified specific assembly-related tasks in which haptic cues affected users' completion time and measures of accuracy. Statistical analysis of the collected data confirmed the significance of haptic interaction in performing simulations of weight recognition, part positioning and manual assembly.

For weight recognition tasks, haptic feedback enabled users to compare the weights of paired models in less time than using only visual perception. This observation confirmed the initial research hypothesis presented in section 4.2. However, the correct identification of weight quantities between two objects is dependent on which hand was manipulating the heaviest model and the sensory modality used. The majority of participants regarded haptic interaction very useful in completing weight comparisons in a virtual environment.

The research concluded mixed results concerning haptics-based interaction for performing positioning tasks in a three-dimensional VR simulation. The addition of haptic feedback had an insignificant effect on user completion times. However, the haptic rendering of contact forces enabled users to position objects at target locations with higher accuracy than using visual approximation. Furthermore, the rendering of resistive forces allowed users to translate virtual components along a specified trajectory with steadier hand motions than tasks that did not provide haptics assistance. The investigation also concluded that user performance is dependent on both the direction of travel and the sensory modality used. Positioning tasks completed along the z-direction without haptic feedback resulted in poor performance evaluations. The majority of participants considered haptic interaction very useful when positioning components in a three-dimensional virtual simulation.

For manual assembly tasks, the research yielded inconclusive results regarding the performance effect of haptic interaction. Although the study participants completed manual assembly tasks in less time when aided by haptics, further statistical analysis concluded this to be insignificant. The majority of the sample population viewed haptic feedback useful in completing manual assembly tasks within a virtual simulation.

The manual assembly experiment also evaluated the performance effect regarding the use of multiple haptic devices. The results of the study show that users were able to complete virtual assembly sequences using one or two-hands in similar amounts of time. In performing two-handed operations, completion times were largely dependent on the dexterity of users in controlling two haptic devices. The majority subjects valued the use of two haptic devices as beneficial.

7.2 Future Work

This investigation provides support for further development and research of haptics-based interaction. The use of haptics for virtual assembly provided performance benefits in some aspects of user operation, but was inconclusive in others. These results are a reflection of designed study and software application, and the involved sample population. Recommendations for future work can potentially resolve these issues and advance the current state of the research.

- Investigate user performance of haptics-enabled virtual assembly in immersive environments such as CAVE system.
- Establish a unified testing environment that accommodates all users in terms of ergonomic factors.
- Compare user performance for completing one and two-handed assembly in real and virtual environments.
- Evaluate user performance in virtual assembly tasks involving joining methods and tools with haptic rendering.
- Investigate the performance effects of additional haptic rendering techniques such as snapping and vibration for virtual assembly.
- Evaluate user performance in haptics-based virtual assembly that features physics-based modeling, constraint-based modeling, and a combination approach.

BIBLIOGRAPHY

Adams, Richard, Daniel Klowden, and Blake Hannaford. 2001. Virtual Training for a Manual Assembly Task. In *Haptics-e*.

PhysX by Ageia: Physics SDK API Reference (Compiled HTML Help file). Ageia Technologies, Inc, Mountain View.

Arsenault, Roland, and Colin Ware. 2000. Eye-Hand Co-ordination with Force Feedback. *CHI Letters* 2 (1):408-414.

Baraff, David, and Andrew Witkin. 2001. Physically Based Modeling: Rigid Body Simulation. Paper read at Siggraph 2001 Course Notes, at Los Angeles, CA.

Bloomfield, Aaron, Yu Deng, Jeff Wampler, Pascale Rondot, Dina Harth, Mary McManus, and Norman Badler. 2003. A Taxonomy and Comparison of Haptic Actions for Disassembly Tasks. Paper read at IEEE Virtual Reality 2003, 2003.

Boothroyd, Geoffrey. 2005. *Assembly Automation and Product Design*. Edited by G. Boothroyd. 2 ed, *Manufacturing Engineering and Materials Processing*. Wakefield: CRC Press, Taylor & Francis Group.

Boothroyd, Geoffrey, Peter Dewhurst, and Winston Knight. 1994. *Product Design for Manufacturing and Assembly*. New York: Marcel Dekker, Inc.

Burdea, Grigore C. 1996. *Force and Touch Feedback for Virtual Reality*. New York: Jon Wiley & Sons, Inc.

Coutee, Adam S., and Bert Bras. 2004. An Experiment of Weight Sensations in Real and Virtual Environments. Paper read at ASME 2004 Design Engineering Technical Conferences and Computers and Information in Engineering Conference, September 28th-October 2, 2004, at Salt Lake City, Utah, USA.

Cruz-Neira, Carolina, Allen Bierbaum, Patrick Hartling, Christopher Just, and Kevin Meinert. 2005. VR Juggler: The Programmer's Guide. Ames, IA: Iowa State University.

Edwards, Gregory W., Woodrow Barfield, and Maury A. Nussbaum. 2004. The use of force feedback and auditory cues for performance on an assembly task in an immersive virtual environment. *Virtual Reality* 7:112-119.

Erleben, Kenny, Jon Sporring, Knud Henriksen, and Henrik Dohlmann. 2005. *Physics-Based Animation*. First ed. Hingham: Charles River Media, Inc.

Fischer, Andrew, and Judy M. Vance. 2003. PHANTOM Haptic Device Implemented in a Projection Screen Virtual Environment. In *Eurographics Workshop on Virtual Environments*. Zurich, Switzerland: The Eurographics Association.

Force Dimension. 2001-2007. www.forcedimension.com.

Frohlich, Bernd, Henrik Tramberend, Andrew Beers, Maneesh Agrawala, and David Baraff. 2000. Physically-Based Manipulation on the Responsive Workbench. Paper read at IEEE Virtual Reality Conference 2000, at New Brunswich, NJ, USA.

Gomes de S., Antonino, and Gabriel Zachmann. 1998. Integrating Virtual Reality For Virtual Prototyping. Paper read at 1998 ASME Design Engineering Technical Conferences, at Atlanta, GA, USA.

Gurocak, Hakan, Sankar; Jayaram, Benjamin; Parrish, and Uma Jayaram. 2003. Weight Sensations in Virtual Environments Using a Haptic Device With Air Jets. *Journal of Computing and Information Science in Engineering* 3:130-135.

Haption. 2007. www.haption.com.

Hollerbach, John M. 2000. Some Current Issues in Haptics Research. Paper read at Proceedings of the 2000 IEEE International Conference on Robotics & Automation, at San Francisco, CA, USA.

Immersion Corporation. 2007. www.immersion.com.

Jayaram, Sankar, Hugh I. Connacher, and Kevin W. Lyons. 1997. Virtual assembly using virtual reality techniques. *Computer-Aided Design* 29 (8):575-584.

Jayaram, Sankar, Judy M. Vance, Rajit Gadh, Uma Jayaram, and Hari Srinivasan. 2001. Assessment of VR Technology and its Applications to Engineering Problems. *Journal of Computing and Information Science in Engineering* 1:72-83.

Jones, M. Gail, Thomas Tretter, Alexandra Bokinsky, and Atsuko Negishi. 2005. A Comparison of Learning with Haptic and Visual Modalities. In *Haptics-e*: North Carolina State University, University of North Carolina at Chapel Hill, University of Louisville.

Kim, Chang E., and Judy M. Vance. 2003. Using VPS (Voxmap Pointshell) as the Basis for Interaction in a Virtual Assembly Environment. Paper read at ASME 2003 Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 09/02/2003 - 09/06/2003, at Chicago.

Kim, Chang E., and Judy M. Vance. 2004. Collision Detection and Part Interaction Modeling to Facilitate Immersive Virtual Assembly Methods. *Journal of Computing and Information Science in Engineering* 4:83-90.

Lin, Ming C., and Stefan Gottschalk. 1998. Collision detection between geometric models: a survey. Paper read at Proceedings of IMA Conference on Mathematics of Surfaces, at Birmingham, UK.

Magnusson, Charlotte, Kristen Rassmus-Grohn, Calle Sjostrom, and Henrik Danielsson. 2002. Navigation and recognition in complex haptic virtual environments - reports from an extensive study with blind users. Paper read at Proceedings of Eurohaptics, 2002.

Massie, Thomas H. 1998. A Tangible Goal for 3D Modeling. *IEEE Computer Graphics and Applications*:62-65.

Massie, Thomas H., and J.K Salisbury. 1994. The PHANTOM Haptic Interface: A Device for Probing Virtual Objects. Paper read at ASME Winter Annual Meeting, Symposium of Haptic Interfaces for Virtual Environment and Teleoperator Systems, 1994, at Chicago, IL.

McDermott, S.D., and Bert Bras. 1999. Development of a Haptically Enabled Dis/Re-Assembly Simulation Environment. Paper read at ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference (DETC1999/CIE-9035), at Las Vegas, NV.

McNeely, William A., Kevin D. Puterbaugh, and James J. Troy. 1999. Six Degree-of-Freedom Haptic Rendering Using Voxel Sampling. Paper read at Siggraph 1999, at Los Angeles, CA.

Mirtich, Brian, and John Canny. 1995. Impulse-based Simulation of Rigid Bodies. Paper read at 1995 Symposium on Interactive 3D Graphics, 1995, at Monterey, CA.

Molloy, O., S. Tilley, and E. Warman. 1998. *Design for Manufacturing and Assembly: Concepts, Architectures, and Implementation*. First ed. Bounday Row, London: Chapman & Hall.

O'Malley, Marcia K., Abhishek Gupta, Matthew Gen, and Yanfang Li. 2006. Shared Control in Haptic Systems for Performance Enhancement and Training. *Journal of Dynamic Systems, Measurement, and Control* 128:75-85.

Ott, R. Lyman, and Michael Longnecker. 2001. *An Introduction to Statistical Methods and Data Analysis*. 5th ed. Pacific Grove: Wadsworth Group.

Salisbury, J.K, and Mandayam A. Srinivasan. 1997. Phantom-Based Haptic Interaction with Virtual Objects. *IEEE Computer Graphics and Applications* 17 (5):6-10.

JMP Software 6.0.0. SAS Institute Inc., Cary.

Sensable Technologies. 2005. OpenHaptics Toolkit version 2.0 Programmer's Guide: Sensable Technologies.

Sensable Technologies. 2007. www.sensable.com.

Seth, Abhishek, Hai-jun Su, and Judy M. Vance. 2005. A Desktop Networked Haptic VR Interface for Mechanical Assembly. Paper read at ASME International Mechanical Engineering Congress and Exposition, 11/05/2005 - 11/11/2005, at Orlando, FL.

Sutherland, Ivan. 1965. The Ultimate Display. *Proceedings of IFIP Congress*:506-508.

Volkov, Sergei A., and Judy M. Vance. 2001. Effectiveness of Haptic Sensation for the Evaluation of Virtual Prototypes. Paper read at ASME 2001 Design Engineering Technical Conferences and Computers and Information in Engineering Conferences, September 9-12, 2001, at Pittsburg, Pennsylvania, USA.

APPENDIX A. USER STUDY FORMS

A.1 Pre-Study Questionnaire

Introduction:

The information provided on this questionnaire will be used to model the demographics associated with the participants of this study. The provided information will be used anonymously and referenced with identification numbers.

Section 1: Personal:

1. Identification Number:

   ____

2. Age:

   ____

3. Gender: Male Female

4. Hand Dominance: Left Hand Right Hand
   Ambidextrous

5. Vision: Perfect Nearsighted Farsighted

6. Occupation:

   ____

7. Educational Background:

   ____

Section 2: Experience:

1. Please indicate the amount of your computer experience in years.
   a. 0 to 5
   b. 6 to 10
   c. 11 to 15
   d. 16 to 20
   e. 21 or greater

2. Please indicate the areas of computer usage that applies to your experience.
   a. Programming (software, web-based, database, etc.)
   b. Virtual Reality
   c. Computer-Aided Design
   d. Data Analysis (Matlab®, Excel®, etc)
   e. Fundamental (word processing, internet, email, etc.)
   f. Other: ____

3. Do you have prior experiences with assembly operations? If yes, please explain.

4. Do you have prior experiences with haptics or similar devices? If yes, please explain.

A.2 Post-Study Questionnaire

Introduction:

The responses provided on this questionnaire will be used to determine conclusions associated with this study. In particular, we are interested in the usefulness of force feedback interaction in virtual assembly applications.

Section 1: Weight Recognition Experiment:

1. How comfortable were you in selecting the heaviest component using just visual information?
   a. Very Comfortable
   b. Comfortable
   c. Neutral
   d. Uncomfortable
   e. Very uncomfortable

2. How comfortable were you in selecting the heaviest component with the presence of force feedback?
   a. Very Comfortable
   b. Comfortable
   c. Neutral
   d. Uncomfortable
   e. Very uncomfortable

3. To what extent did force rendering assist in the weight recognition of components?
   a. Very useful
   b. Useful
   c. Neutral
   d. Useless
   e. Very useless

Section 2: Part Positioning Experiment:

1. In the trials that did not have force rendering, which translational direction was the most difficult to position the virtual object?
    a. X-direction
    b. Y-direction
    c. Z-direction
    d. All
    e. None

2. With the presence of force rendering, which translational direction was the most difficult to position the virtual object?
    a. X-direction
    b. Y-direction
    c. Z-direction
    d. All
    e. None

3. To what extent did force rendering assist in placing to virtual object in its final location?
    a. Very useful
    b. Useful
    c. Neutral
    d. Useless
    e. Very useless

Section 3: Assembly Simulation Experiment:

1. In the assembly sequences that did not have force feedback, please identify the ease/difficulty of completing the task.
    a. Very Easy
    b. Easy
    c. Neutral
    d. Difficult
    e. Very Difficult

2. Please indicate the ease/difficulty of task completion when force rendering was provided.
    a. Very Easy
    b. Easy
    c. Neutral
    d. Difficult
    e. Very Difficult

3. To what extent was force rendering beneficial in regards to assembly task completion?
    a. Very useful
    b. Useful
    c. Neutral
    d. Useless
    e. Very useless

4. Would you consider the use of multiple haptic devices a significant benefit or a burden to the simulation experience? Please explain.
    a. Benefit
    b. Neutral
    c. Burden

Section 4: Device Manipulation:

1. Were there any difficulties encountered with using the devices? Please explain.

2. Were you able to achieve all of the desired motions with the device based on user input? Please explain.

3. To what extent does the physical separation of hand and visual workspaces limit the effectiveness of the simulation? Please explain your response.
    a. Greatly affects the effectiveness of the simulation
    b. Somewhat affects the effectiveness of the simulation
    c. Does not affect the effectiveness of the simulation

4. To what extent does the magnitude of force rendering affect the simulation? Please explain
    a. Largely affects the simulation
    b. Somewhat affects the simulation
    c. Does not affect the simulation

5. Based on the software application that you have experienced, are there any possible improvements that can be made? Please explain.