HUMAN FACTORS AND TELEROBOTICS: TOOLS AND APPROACHES FOR DESIGNING REMOTE ROBOTIC WORKSTATION DISPLAYS

by

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DESIGN OF AN INTEGRATED SPACE STATION ROBOTIC WORKSTATION

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A methodology is created for designing and testing an intuitive synthesized telerobotic workstation display configuration for controlling a high degree of freedom dexterous manipulator for use on the International Space Station. With the construction and maintenance of the International Space Station, the number of Extravehicular Activity (EVA) hours is expected to increase by a factor of four over the current Space Shuttle missions, resulting in higher demands on the EVA crewmembers and EVA crew systems. One approach to utilizing EVA resources more effectively while increasing crew safety and efficiency is to perform routine and high-risk EVA tasks telerobotically. NASA's Johnson Space Center is developing the state-of-the-art dexterous robotic manipulator. An anthropomorphic telerobot called Robonaut is being constructed that is capable of performing all of the tasks required of an EVA suited crewmember. Robonaut is comparable in size to a suited crewmember and consists of two 7 DOF arms, two 12 DOF hands, a 6+ DOF "stinger tail", and a 2+ DOF stereo camera platform. Current robotic workstations are insufficient for controlling highly dexterous manipulators, which require full immersion operator telepresence. The Robonaut workstation must be designed to allow an operator to intuitively control numerous degrees of freedom simultaneously, in varying levels of supervisory control and for all types of EVA tasks. This effort critically reviewed previous research into areas including telerobotic interfaces, human-machine interactions, microgravity physiology, supervisory control, force feedback, virtual reality, and manual control. A methodology is developed for designing and evaluating integrated interfaces for highly dexterous and multi-functional telerobots. In addition a classification of telerobotic tasks is proposed. Experiments were conducted with subjects performing EVA tasks with Space Station hardware using Robonaut and a Robonaut simulation (also under development). Results indicate that Robonaut simulation subject performance matches Robonaut performance. The simulation can be used for training operators for full-immersion teleoperation and for developing and evaluating future telerobotic workstations. A baseline amount of Situation Awareness time was determined and reduced using the display design iteration.

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1 Introduction

A vision must be much more than a project, even a big project.
- Robert S. Walker, FINAL FRONTIER, April 1989.

1.1 Motivation

With the construction and maintenance of the International Space Station, the number of EVA hours is expected to increase by a factor of four over the current Space Shuttle missions, resulting in higher demands on the EVA crewmembers and EVA crew systems. One approach to utilizing EVA resources more effectively while increasing crew safety and efficiency is to perform routine and high-risk EVA tasks telerobotically. NASA is working to make 50% of all EVA missions conducted telerobotically by the year 2004. In response, NASA's Johnson Space Center is developing the state-of-the-art dexterous robotic manipulator. An anthropomorphic telerobot called Robonaut (shown in Figure 1.1 and 1.2) is being constructed that is capable of performing all of the tasks required of an EVA suited crewmember. Robonaut has been under construction since 1996 and reached its current anatomical configuration in 2000. Robonaut is comparable in size to a suited crewmember and consists of two 7 DOF arms, two 12 DOF hands, a 6+ DOF "stinger tail", and a 2+ DOF stereo camera platform.

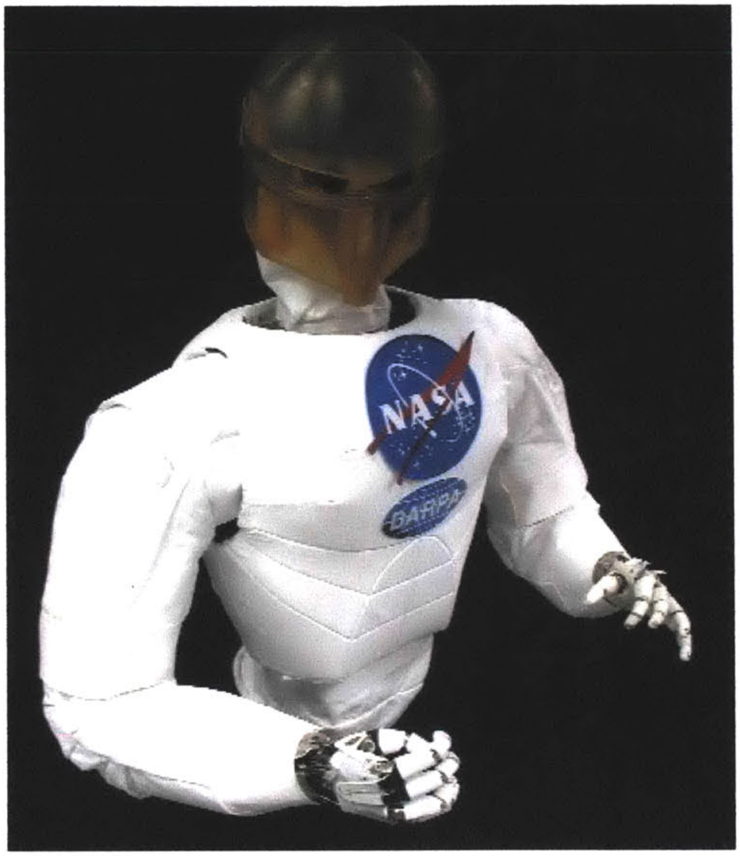


Figure 1.1 Robonaut

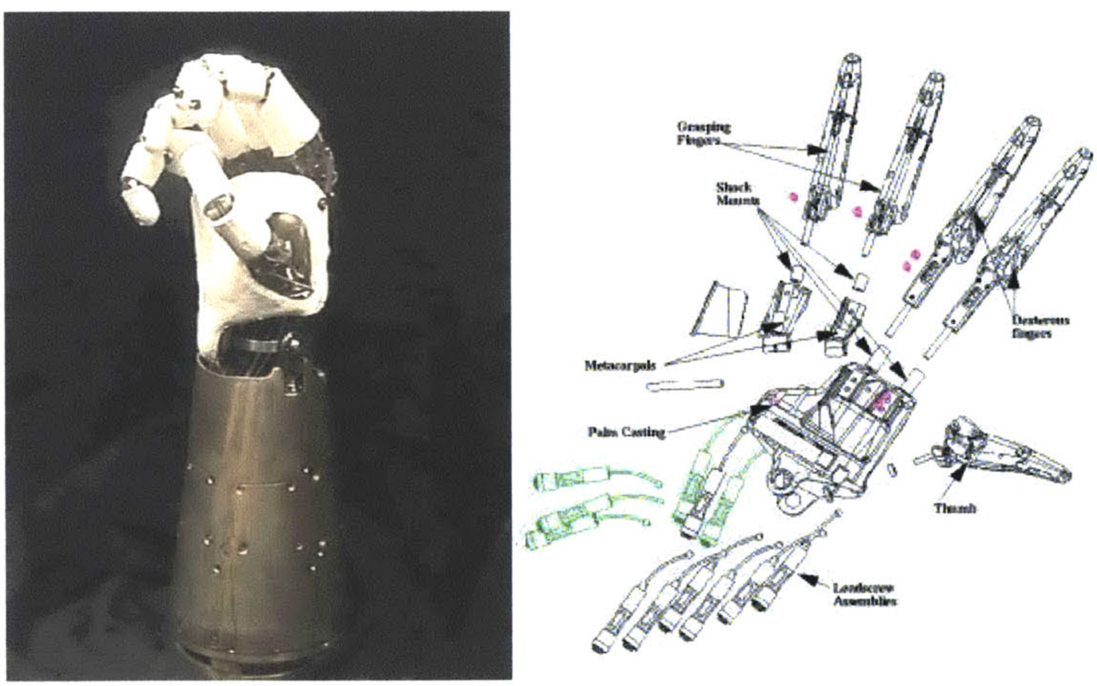


Figure 1.2 Robonaut hand

In his paper on human performance in teleoperation, Lumelsky envisioned advancing EVA capabilities by considering "EVA crews and telerobots as semi-interchangeable work systems [1990]." He further suggests that the EVA crews and telerobots could, for space station EVA operations, be considered as a team, each retaining their own unique advantages and disadvantages for a given task. Any redundancy in capabilities would allow for greater flexibility and failure tolerance. Given this objective, the need for state-of-the-art technology is apparent. The Robonaut concept document explains the need for such an advanced technology. It states "the existing Space Station robots (SPDM and SSRMS) are inadequate substitutes for an astronaut because they: (1) require additional special alignment targets and grapple fixtures; (2) are too large to fit through tight EVA access corridors; and (3) do not possess adequate speed and dexterity to handle small and complex items, soft and flexible materials, and most common EVA interfaces."

In addition, the current robotic workstation for Space Station robots, consisting of flat panel displays and 6 DOF hand controllers, is insufficient for controlling highly dexterous manipulators that require full immersion operator telepresence. For Robonaut, operators are required to have sensors and displays over the majority of their body in order to command the robot successfully. While hand controllers may be useful for moving Robonaut to different worksites on the Space Station, completion of complicated EVA tasks will require control inputs that may be provided by the movements of an IVA crewmembers hands, arms, head and torso. As the majority of the operators body is involved in sensing and commanding the robot in this case, we utilize the term "full immersion" to distinguish this type of operation from simple hand-controller input devices, for example.

The workstation must be designed to allow an IVA operator to intuitively control numerous degrees of freedom simultaneously, in varying levels of supervisory control and for all types of EVA tasks. This type of full immersion operation places greater demands on the human, particularly in terms of Situation Awareness and workload. The operator must be aware of their entire body at all times, as any movement will be tracked and act as a command stream to remote hardware. This presents a significant challenge to the designer of displays and feedback mechanisms. As most limbs are being tracked, they cannot be used to toggled between displays, used to operate keyboards or joysticks as readily, etc., hence voice commands become an important alternative to mouse inputs, and somatosensory feedback cannot interfere with sensor hardware. It is important therefore, to understand how the human operates in this full immersion environment so that every effort can be made to enhance the safety and ease of operation, increase performance, reduce errors and keep workload to a controllable level.

Figure 1.1 shows a schematic of the human-robot control loop. The robot state information is sent to the human operator who then acts on the robot through the teleoperation hardware. However, it is not necessary to relay to the operator every aspect of the robot state. Information that is critical to transmit to the operator will be filtered and sent through various sensory output channels. Sensory output channels include visual, auditory, force and tactile. The challenge is to determine which information should be presented over the particular sensory channels to the operator, and to define the appropriate interface. Thus, the motivation is to display all necessary control and sensory information to the operator effectively to optimize performance - without inducing error, fatigue or high workload.

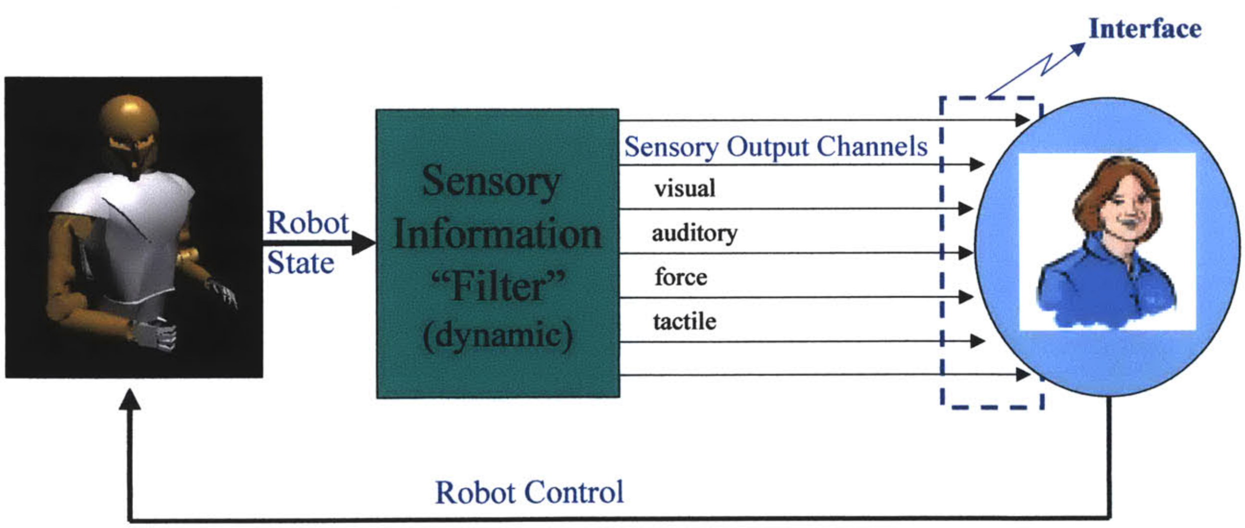


Figure 1.1 Schematic of human-robot control loop

1.2 Thesis Objectives

Significant research (discussed in Chapter 2) has been conducted in human factors areas such as telerobotic interfaces, human-machine interactions, supervisory control, force feedback, virtual reality, and manual control. However, many of the tasks performed in the experiments described in the literature do not capture the variety and complexity of the tasks required of an EVA crewmember. In most studies, optimal workstation components are determined based on performance of discretized subtasks without regard to the transitions that the operator must go through between tasks performed sequentially. In addition, much of the research focuses on a particular hardware or software aspect of the workstation without addressing the synthesis of components required to tackle the human factors and controls issues of the system as a whole. Finally, the few groups that have looked at workstations as a whole either have not had to control as many degrees-of-freedom as Robonaut demands, or have controlled high degree-of-freedom robots that lack the dexterity of Robonaut, and therefore employ hand controllers. The goal of this research effort is to design and test an intuitive synthesized telerobotic workstation display for controlling a high degree of freedom dexterous manipulator for use on the International Space Station.

The objectives for this thesis also consist of determining human performance characteristics during full-immersion teleoperation and identifying methods to be used for development of new interfaces, displays and aids for the telerobotic workstation. This includes studying teleoperator performance, identifying performance roadblocks, and designing and testing displays to reduce these roadblocks thereby increasing operator performance (performance can be measured in a variety of ways and in this case includes task time and number of errors).

1.3 Research Statement

The approach to accomplish this goal is threefold:

- Develop a simulation tool for designing workstation displays
- Test and validate the simulation tool through comparison with robot performance
- Design a workstation displays through an iterative process involving integrated EVA tasks using the validated Robonaut simulation

The testing process described in this document involves not only an initial display test, but a refinement of the displays and a subsequent verification test. The goal is to allow the experimenter to gather the knowledge base necessary to construct Situation Awareness displays and aids for the workstation and to refine and test these displays and feedback mechanisms in a non-intrusive manner and with minimal cost to delicate robot hardware. Creating a development testbed is a key element in this research. In systems engineering, it is desirable to use a single analysis tool that has the capacity to conduct trades between system variables. The simulation presented herein is designed to that end to act as a design tool that can be used for iterations of the display design process. It is hypothesized that a simulation of the robot hardware will yield similar behavior characteristics as the robot, allowing researchers to develop workstation displays and aids with a variety of benefits. First, a simulation has the benefit of unlimited availability, whereas time on the robot hardware is limited. Second, minimal personnel are required to run a computer simulation. In its current configuration, a minimum of three people is required to activate and run the robot hardware. Finally, there is no wear and tear on the robot system using the simulation, therefore there is no "cost" for operator error. For safety reasons, only after the refinements have been tested on the simulation should they be available for robot applications. As these are the first set of experiments conducted using the simulation, its ability to match Robonaut's performance has not yet been quantified, nor has its scope and/or limitations.

1.4 Thesis Overview

Previous research in various disciplines relevant to telerobotic workstation design is discussed in Chapter 2, Background. In Chapter 3, Robonaut, teleoperation and Robosim are introduced. The EVA basis task classification and display design paradigm are discussed in Chapter 4. Chapter 5 covers the experimental methods including subject, hardware, software, task protocols and data analysis methods for a preliminary integrated telerobotic study. Chapter 6 describes the Robosim evaluation testing, and chapters 7 and 8 continue with two display design iteration experiments. Finally the conclusions and contributions of the thesis are presented in Chapter 9.

2 Background

There is one thing even more vital to science than intelligent methods; and that is, the sincere desire to find out the truth, whatever it may be

- Charles Sanders Pierce

In 1994, Sheridan published perhaps the most complete and general overview of each of the critical human factors issues associated with remote manipulation, surveying to date some of the advances made in each of the areas of concern. These areas include proprioception, vision systems (both video and virtual), sensory substitution, manual control and time delay and presence. These topics, and others, were studied in detail for this research effort. The discussion presented here first provides an overview of how humans perceive their environment through various sensory channels. The visual system is singled out in particular, as it bears great relevance to display design. Next, issues relevant to the practice of teleoperation are discussed, including the teleoperators' sense of presence at the worksite, and degradation of that sense due to signal time delays between the teleoperated robot and the operator. A series of topics related to methods of providing feedback of information to the operator, and obtaining evaluations of the system from the operator are also discussed. To conclude, the topic of human-computer interaction design is presented.

2.1 Human Proprioception and Performance

In order to optimize the design of a space teleoperation workstation, it is valuable to identify an overall design driver. In this case, the variable we wish to optimize is Situation Awareness (SA). While the definition of SA has been hotly debated in the past decade [Endsley, 1995], the most relevant thing to note at this point is that the metric of SA is not absolute, rather it is dependent on the task, user and supervisory control level. As a result, it is important to understand the mechanism by which humans sense information from the environment and arrive at various levels of SA. In turn, we must also recognize any differences in the way these mechanisms operate in microgravity and how elicited control actions differ on the ground and in orbit.

In the Earth's 1-G environment, perception of position and orientation is determined by the CNS through receiving and interpreting redundant information from the body's individual sensory systems: the visual, vestibular and somatosensory systems (skin, muscle and joint sensors). However, exposure to weightlessness can lead to conflicting sensory cues, resulting in decreased SA [Rochlis, 1998]. Cues from sensory systems that are not degraded are then weighted more heavily in determining SA. Namely, vision becomes the most relied upon sense during space flight. In order to establish a sense of presence, the operator must be able to gain SA through a workstation comprised of displays and input devices, rather than through direct interaction with the worksite. Therefore, understanding that somatosensory and vestibular cues are degraded during teleoperation, efforts must be made to provide the operator with sufficient cues either through other sensory channels, or through sensory substitution. Examples of sensory losses due to remote operation are of course, loss of haptic feedback with manipulated objects, and loss of motion cues due to being constrained to operate at a fixed location IV. Thus, EVA astronauts trained to perform tasks in space rely on feedback that will either be degraded or absent IV.

Young has conducted many studies on human performance in space including the effects of space flight on vestibular reflexes and perception [Young, 1995], neurovestibular adaption to weightlessness [Young & Merfeld, 1995], and tactile influences on astronaut visual spatial orientation [Young et.al. 1996. One, perhaps subtle, cue that the vestibular system provides to increase our SA is a sense of perceived self-motion, or vection. He confirmed that the delay in the onset of vection could be a result of degraded vestibular function on orbit. In regards to the increased reliance on visual cues, he noted that in determining perceived self-motion in space, the presence of any tactile cue inhibited the dependence on the visual system. He also noted that is desirable to determine alternate sensory channels through which to convey feedback information, as the visual system is in most cases overloaded between primary task performance and visual display integration. Merfeld [1995,1996] has also researched the ways humans estimate acceleration in the absence of gravitational cues, as well as induced motion sensations. As an example of how this is relevant to teleoperation, one of the current advanced teleoperation system at NASA's Johnson Space Center, the DART/FITT testbed, has subjects seated in a chair that is able to swivel about its base. If the operator turns the robot to the right, the chair likewise spins to the right, giving the operator a vestibular self-motion cue that helps to maintain a sense of presence throughout the rotation. This type of rotating chair may not be practical or even possible to have onboard the space station; thus understanding what can be done to compensate for a lack of self-motion cues during space flight can lead to higher operator SA.

In addition to ensuring that the operator has sufficient SA to accomplish the task, we must also ensure that performance levels of the IVA operator are comparable to that of the EVA operator. Work on general human performance characteristics in space operations has been surveyed by Chandlee [1993], Akin [1986], Ranninger [1997], Lathan [1996], Pate [1996] and Likowsky [1996]. Lathan quantified cognitive differences for motor control during space flight and found no significant loss in cognitive processing. Akin and Ranninger looked at ways to quantify performance and fatigue during EVAs and Pate likewise points out individual attributes that lead to fatigue and performance degradation, such as training, motivation, prior experience, posture, stature and strength. An important design driver to remember is that Robonaut has been tasked to emulate an EVA astronaut, and not a ground operator; performance must only be as sufficient as a suited crewmember. In terms of evaluating Robonaut and the workstation, crew must be reminded that the performance should not be compared to Earth based, manual operation.

2.2 Vision Systems

Sheridan [1994] explained, "The most important sensory communication channel for remote manipulation is vision." As we have just seen, this is also true for space operations. Wlech and Warren [1986] discovered that in terms of object recognition, vision was more valuable (weighted more heavily by the CNS) than haptic touch, and that when the two senses were in conflict, vision dominated. They also discovered that the reaction time to a visual stimulus was slower than that to a tactile stimulus, which has relevance to the design of emergency alerting protocols. It also has relevance to operator-induced instabilities due to force reflecting and visual feedback in the presence of time delays (discussed in section 3.4). As a result of the higher CNS weighting of visual cues, the designer must take care not to overload the operator with visual displays assuming that other sensory information will be disregarded. The key is to provide non-conflicting cues through other sensory channels (sensory overload and substitution will be discussed in the next section).

Since visual feedback is critical in space teleoperations, the visual display is perhaps the most important component of the workstation. Loss of depth perception is the reason why telemanipulation performance does not equal direct manipulation performance [Sheridan, 1994]. Massimino and Sheridan [1989] compared direct vision with video for a peg-in-hole task and concluded that as long as the visual field of the manipulated object was the same for both viewing conditions, neither was significantly better than the other was. Decreased SA can result in either case unless there is a one to one spatial correspondence between the operator control inputs and the perceived manipulator motion [Smith and Stuart, 1993]. However, in the case of a reduced visual field, performance times were faster with direct vision. This makes a case for a wide field of view display, whether it is a video screen or a head mounted display (HMD). If wide field of view, high resolution and high update-rate visual displays are not available, computer aiding can assist in task completion by providing addition depth perception and perspective cues to the operator.

Vidov [1993] conducted experiments that investigated tradeoffs between frame rate, grayscale and resolution for bandwidth limited communication. Results found that color was not always crucial for high performance, but depended on the task to be completed. He also commented that stereoscopic effectiveness declined at a distance of several meters, but was good for closer dexterous manipulation tasks since it conveyed both direction and speed. Liu et.al. [1993] studied the use of HMDs for teleoperator performance improvements and noted that very little research has been conducted as to the overall effectiveness of HMD systems, rather the studies focused mainly on the tradeoffs of various design parameters as mentioned above. Liu and his group chose to explore these issues for 3-D tracking and pick-and-place tasks. They found values for minimum update rates for both experienced and inexperienced users and concluded that experienced users were better able to adapt to degraded visual conditions. Although they concluded that HMD parameters can be degraded without significant loss of performance and that the extra computational resources can be used for graphical predictive displays, the experiment was not sufficient to make global statements about it's effectiveness. In fact, no research group has been able to conclude if overall, video is better or worse than HMD; choosing which system to use for experiments seems to depend on other factors such as cost, weight, size, application, etc. Tiring and soreness of the eyes has been sighted as a performance degradation resulting from long duration tasks using video screens or HMDs but again, the two systems have not been quantitatively compared.

Another factor in the design of the vision system is head tracking. Head tracking is implemented in order to give the operator a greater sense of presence at the remote environment, continuity between the familiarity of direct vision and remote vision (such as motion parallax cues), and also to free him/her from having to manually adjust the viewing angle. Head tracking can be combined with either an HMD or a video screen display, however in the presence of a time delay (discussed in section 3.4), it can actually do more harm than good.

2.3 Sensory Substitution

Sensory substitution (SS) can be explained as providing information to the CNS usually sent through one sensory channel via a different sensory channel. A simple example would be the act of the blind reading Braille—information normally presented through visual feedback can be presented through haptic feedback. Patrick [1990] developed a tactile fingertip display for remote manipulation and studied the relationship between teleoperation and SS. He notes that a disadvantage of some sensory feedback systems is the amount of training required before proficiency is attained. He also points out two important distinctions between displays, reactive vs. non-reactive, and forcing vs. non - forcing. A reactive display provides information to the user on the forces applied at the end effector (such as a force reflecting leader-follower manipulator). A simple joystick only applies feedback of the input motion, not of the reaction of the environment. A forcing display applies a steady force to a part of the body, whereas a non-forcing display (such as a visual or auditory display) does not. Patrick concluded that visual in conjunction with tactile feedback provided a small but significant performance increase. In other words, little is gained by adding tactile feedback to an adequate visual display. He also found that tactile feedback was superior to visual feedback when the information content of the two signals was the same (recall that humans react faster to tactile than to visual stimuli).

Massimino conducted his Ph.D. research on sensory substitution for force feedback in space teleoperation [1992], using both vibrotactile and auditory displays. SS was used to present presence and magnitude of both instantaneous and sustained object contact forces (primarily for peg-in-hole tasks), as well as force direction in some instances. He concluded a number of relevant results:

1) SS alone allowed for task completion with fully obstructed visual views

2) SS increased performance with degraded visual cues for depth perception critical tasks

3) SS displays had a lower detection threshold for force than force reflecting (traditional) feedback (allows one to increase the feedback gain for tasks where early force detection or high sensitivity is critical)

4) Traditional force feedback resulted in significantly smaller task completion times (force information did not have to be interpreted, as it was applied intuitively and directly to the hand and arm where the control commands originated)

5) In the presence of a time delay, SS may be used, as it does not introduce instabilities

6) Auditory displays are useful for representing accurate force direction information

When comparing the auditory and tactile force direction display, Massimino noticed an interesting phenomenon. The information content was higher in the auditory display, which proved to be both a help and a hindrance depending on the situation. In cases where other sensory information is severely degraded and the operator needs as much feedback as possible, displays with the highest information content should be used. However, if being used in conjunction with other sufficient displays, task performance can actually decrease since the operator is overloaded with display information. Massimino cites Oatman's [1976] research into the way human's process simultaneous inputs from multiple sensory channels. The most recent theory on how humans deal with many signals competing for attention explains that there is a channel for each sensory modality that gathers the input. Information from all channels flows into a limited capacity central processor that elicits a response. There is a feedback path between any attenuated channel and the processor such that the channel information is filtered peripherally. Therefore, the central processor decides which channels to attenuate and activates a filter for that channel. Oatman made the distinction that focusing attention, while helpful in keeping irrelevant stimuli from interfering, does not mean that the irrelevant stimuli will not be processed. In another study, a group of researchers created a force-torque graphical display for use in a simulated SRMS operation [Bejczy et.al., 1981]. They found that the display alone lead to faster completion times that with a visual view of the task alone, however when both were used, performance degraded. The conclusion was that the workload was excessive, as the operator was overloaded with display information.

If SS is in the form of haptic feedback to the hand, the operator may adapt to a continual forcing display. The skin as a force sensor is highly reflexive (a tap on the shoulder causes you to turn your head towards the shoulder in response), adapts quickly to stimuli but can sense changes in applied force [Rochlis, 1998]. In addition, a reactive display can elicit motor responses from the operator. For example, consider a force reflecting hand controller moving a robotic arm that strikes a surface in the remote environment. The operator, upon sensing this large magnitude force change, may reflexively let go of the manipulator, or move it quickly in the opposite direction. Force or haptic feedback can also become problematic in the presence of a time delay, as will be discussed in the next section.

2.4 Time Delay

Transmission delays arise from not only due to the finite speed of light, but from limited available bandwidth on data transmission lines, and computer and relay satellite processing time. Time delays in signal transmissions can change the very nature of an operator's control strategy, decrease task performance, increase task times and increase operator-induced instabilities. These instabilities can result from delays in visual feedback, force feedback, or both. Delayed visual information from the remote environment can cause the operator to generate motor commands that are not appropriate for the current status of the robot. Experiments conducted in 1965 by Ferrell proved that the human operator adopts an open-loop "move and wait" strategy, making a small corrective action and then waiting to see it's effect before making the next movement. The method did not lead to unstable control movements, or add to the operators emotional stress level, and was used so consistently in fact, that he was able to generate two equations which predicted the average task completion time. The relationship between the delay time and completion time was relatively linear and the performance dependent on the required accuracy, as well as the delay time. However, the move-and-wait strategy is useful at the expense of time, as task times are greatly increased using this movement strategy.

Delayed visual information can manifest itself as slowed video feedback to a video screen, or as a mismatch between head tracking motions and an HMD display, leading to operator disorientation. Different amounts of delay can be tolerated for different types of tasks. Some have suggested that for tracking targets with head movements, performance does not suffer until delays grow in excess of 1s, at which point the performance degrades quickly [Liu, 1993]. Research into effective computer display aiding has focused on creating predictive end effector position displays to compensate for time delay induced instabilities. Other visual readout displays including grids and wire frames for navigation and depth perception purposes, are also commonly used [Matsumoto, 1992; Bejczy and Kim, 1990; Lee, 1993;Hine et.al., 1995; Blackmon & Stark, 1996]. Predictive displays assist in the presence of time delays by telling the operator "this is what will happen, given the current initial conditions of the vehicle or teleoperator" [Sheridan, 1994, 1993]. A telerobotic predictive display uses real-time simulation of the telerobot kinematics and dynamics to extrapolate where the manipulator will be at some finite time in the future and overlays a computer-generated graphic of the manipulator onto the visual scene. For 2-D pick-and-place and peg-in-hole tasks, decreases in task times of up to 50% have been recorded.

Sheridan in his review of previous research into time delay in teleoperation concluded that there were at least four limitations of the utility of a predictor display. First, the success of the display is limited by the fidelity of the kinematic and dynamic models of the telerobot. Second, calibrating the display (in position, orientation and scale) to the video is critical. Third, it is difficult to match predicted depth to directly observed depth; therefore the display is not useful for movements into and out of the image plane. Finally, predictive displays do not conform well to motions when either the video is blocked, or where the movements are small compared to the calibration errors (such as peg-in-hole tasks). A Virtual Environment Vehicle Interface (VEVI) was designed for planetary rover operations (which suffer large time delays) that included two graphic overlays and a predictive display [Hine et.al. 1995]. In addition to a bird's eye view of the rover, there was a navigation grid hovering in the scene at a constant height above the scene, to aid in navigation. These types of computer-generated displays and overlays cost the operator both mental workload and computational time. In addition, operator preference is certainly a variable to consider when providing such displays. For a telerobot such as Robonaut, a predictive display may only be useful for large in-plane motions, whereas another form of visual feedback (perhaps an alphanumeric display) would be necessary for movements that required accurate depth perception.

Instability can also result from reactive and forcing displays [Kazerooni & Snyder, 1992; Patrick, 1990; Massimino, 1992, Sheridan, 1993, 1992]. Imagine using a force reflecting hand controller to command a leader-follower manipulator. If the follower manipulator strikes a surface, the force reflecting hand controller will signal this disturbance to the leader and the operator will make a reflexive control action. Unfortunately, in the presence of a time delay, it will be the wrong action. Over time, the mismatch drives the system unstable [Das et.al., 1992; Kazerooni, 1995; Massimino, 1990; Sheridan 1993, 1994; Liu, 1993]. Massimino concluded in his experiments that passive sensory substitution could be used in the presence of a time delay to improve operator performance without inducing instabilities.

2.5 Presence

The workstation designer provides the operator with input devices and displays designed to create a sense of presence at the worksite. It is important to note that telepresence is not the same as virtual reality, although the same hardware can be used for both. Telepresence seeks to "put" the user in an actual remote location, whereas an operator is immersed in a computer-generated environment to create a virtual reality [Logan]. From a performance standpoint, researchers have suggested that the human capability for orienting and motion planning in space (often a measure of SA and/or presence) is limited by their ability to interpret the various sensory inputs [Anderson, 1991]. Sheridan

[1994] theorized that there were three independent determinants of presence: 1) extent of sensory information 2) control of relation of sensors to environment and 3) ability to modify physical. These formed an orthogonal set of axes upon which you could represent lines of constant information flow. The lines suggested that information channels are better suited for control of sensors and environmental modifications than for higher resolution displays. Psotka & Davison [1996] suggested factors contributing specifically to virtual environment presence such as interactively, fast update rate, high image complexity, engaging, 3D sound, HMD, stereoscopic, large field of view and head tracking. They attempted to discover other cognitive factors to suggest one's susceptibility to feeling immersed in a virtual environment such as claustrophobia, dream content and distractibility.

Slater and Wilbur [1997] make a distinction between presence and immersion. They claim that immersion is a description of the extent to which computer generated displays provide an inclusive, vivid, extensive, proprioceptively matched illusion of reality, and a plot (or sense of story and interactively). They introduce the term "matching" to describe the correlation between the operator's feedback about movements generated at the worksite, and the information presented on the display. Immersion is therefore an objective and quantifiable description of what the system can provide. Presence on the other hand, is a state of consciousness that can be evaluated both subjectively and objectively. Observable behavioral phenomenon can be correlated with behavioral similarities in virtual environments. Immersion, they explain, is what is associated with task performance, not presence. In reviewing Sheridan's theory of orthogonal attributes, Slater and Wilbuy offer that his axes correspond directly to 1) elaboration of vividness, 2) matching and 3) plot, respectively. Other attributes mentioned previously can be added as additional orthogonal axes.

In the entertainment industry, presence in provided to amusement park attendees through a combination of visual, tactile and vestibular displays. Riders sit in a cabin that is moved hydraulically in sequence with a visual picture to give the illusion that the rider is actually traveling within the virtual scene presented to them. These rides provide a strong sense of self-motion as the movement of the cabin gives vestibular cues, pressure cues to the body as they move about in the seat, as well as a visual cue. Other virtual reality arcade games have players standing or seated on moving platforms while wearing HMDs for the same purpose. Of course, different players and riders are affected to different degrees, as Pstoka and his group attempted to explain. Essentially, the Robonaut workstation seeks to present a similar sense of presence to its operator.

2.6 Subjective Ratings & Workload Assessment

"There is no agreed-on set of measures for any human performance task and setting. Instead, the investigator must select from dozens of possible measures" [Muckler, 1992]. The problem of quantifying performance, workload and SA is one that remains unanswered. The process, however, that of selecting measures, collecting, analyzing and interpreting data, is consistent. Even objective workload metrics such as task times, errors, accuracy, etc., are not immune to outside influences such as emotional state, experience level, or experimenter bias. Furthermore, subjective and objective measures of workload do not consistently agree. Muckler suggests five characteristics that a workload assessment scale should possess to increase its utility: relative simplicity, adequate validity, sufficient reliability, appropriate precision, and generalizability. The question of precision concerns not only how well the workload metric can correlate to other objective measures, but also to the ability to pinpoint the source of the workload. The current industry accepted workload scales ask subjects to evaluate the system as a whole, rather than in parts. Although the system is being evaluated in an integrated fashion, which on the surface seems preferable, it is not possible to determine diagnostic information from these ratings, as mentioned previously. If a system scores low on a controllability scale, it indicates only that there is a problem, not the source of the problem. For example, measuring the workload associated with doing a set of math problems in a given time limit by evaluating subject performance on a secondary task would yield several interesting points. As the problems became more difficult, the secondary task performance would decrease. The number of mistakes that the subjects made on the problems could be measured, however, there is no way to distinguish if the mistakes were made because the problems were too difficult for the subject, or if it was because the workload was too great. This scenario is directly analogous to designing the task space for a teleoperator. How can the researcher distinguish between increased workload, and increased task difficulty? Arriving at one number to describe the system is done in part to gain an overall indication of the utility and controllability of the system being tested, and for ease in comparing results across disciplines and system types.

On the surface, one solution would be to ensure that all of the tasks were of equal difficulty, but this is not a simple feat. This is certainly true for Robonaut given the large numbers of degrees of freedom that the operator has at their disposal, and because task difficulty could vary from subject to subject. Additionally, in trying to perform realistic EVA tasks with transitions, it becomes nearly impossible to predict how each subject will move the robot body through the task. If you constrain the task so that the subjects must all operate Robonaut in the same manner, the potentially revealing intra-subject differences would be masked. If the desire is to look at changes in workload with varying degrees of freedom, the tasks must be compared across all degrees of freedom. The nature of workload measurements is such that tasks should be something that the operators can do well, as opposed to simply complete. Without a time constraint, even the most complex of EVA tasks can be performed with low workload. To get a more accurate measure, either the time must be constrained, or the tasks must be constrained. For complex, multi-component systems such as telerobotic workstations, it is essential that the source of the workload can be assessed without having to test or re-test each individual component. By checking the subjective workload at every level of the design process assures that those sources can be identified and isolated.

Some of the characteristics that existing rating schema seek to measure that relate to SA include memory, perceptual abilities, cognition, personality, and spatial abilities [Bolstad, 1991]. Unfortunately, the relation between SA and workload remains undeveloped. In order to use SA as a design variable, this relationship must be discovered.

2.7 Feedback Mechanisms

For the teleoperator, there is a certain set of information required to complete a task at the same performance level that would be achieved if they were located at the worksite. The following discussion assumes that no less than stereo vision will be supplied to the user through a helmet-mounted display. The information fed back to the user must intuitively give additional or redundant cues as to the state of the robot at the worksite, and enhance the user's feeling of presence. In addition, it must not contribute to instability in the presence of a time delay, overload the user or any particular sensory channel, or elicit unwanted operator control inputs.

The sensory channels that are available to the designer include visual, auditory, tactile and vestibular. The type of information that could be provided includes the following:

- Robot absolute and relative position and orientation
- Force and Torque exerted by the robot
- Linear and rotational velocity of the robot limbs and body
- Contact between robot hand and limbs and object in the workspace
- Proximity of the robot limbs to an object in the worksite
- Alert information
- Kinesthesis (self-motion) information

Not all of this information would be appropriately provided through every sensory channel. The designer must decide which mechanism is best for a given information type. Examples of how each of these information types would be provided through a particular sensory channel are discussed below.

2.7.1 Visual Displays

Visual displays presented within the operators helmet mounted display would be of either the instrument or overlay variety. That is to say, either the operator must direct his gaze away from the primary task or foveal region; or else the graphical display is overlaid on top of the primary gaze direction, as in a heads-up display. Human visual acuity depends upon factors such as brightness, size of object, exposure time and of course, position on the retina. The highest region of acuity for fine detail is when the image is focused on the fovea, spanning only one minute of arc, and whose image quality decreases rapidly with lower light levels, or vibration. Foveal vision is responsible for discerning the detail, shape and pattern of a visual target. The ambient or peripheral region, on the other hand, determines relative motion and position. Many of the body's other processes that determine spatial orientation (such as vestibular cues and haptic cues) also contribute to the visual perception of motion and position. Unlike foveal vision, peripheral is less sensitive to changes in ambient light levels. These differences suggest that a display that contained alphanumeric or fine detail information would be best suited as an overlay. If such a display were located outside of the main field of view, the operator would have to shift his gaze away from the primary task to read and interpret the display. It has been suggested that as much as 90% of visual stimulation is obtained from peripheral vision without conscious effort. If the peripheral vision is well suited for detection of motion and luminosity, it should therefore be exploited to present information that requires little mental processing, such as an alert or an analog display.

Peripheral vision plays an important role in manual control theory. Currently, helmet-mounted technology is limited in the field of view that can be provided to the user (typically only 30 degrees). Unfortunately, without a peripheral vision cue, the time before a potentially hazardous or relevant stimulus is in view may be too short to react. In this way, peripheral vision acts like a predictive display, increasing the amount of lead that the human can generate in manual control inputs.

Video flat panel screens may also be used in conjunction with HMDs to house task, robot, and system controls and information. Table 1 highlights some of the pros and cons of various vision systems that are available for use with Robonaut.

Table 2.1 Visual Display Configuration Options and Attributes

	PROS	CONS
HMD	1) Compact 2) High sense of presence 3) Can overlay computer panel displays	1) Limited field of view 2) Must take on and off (or flip visor up) to actuate switches or other controls, degrading presence and expending more task time 3) Must switch back and forth to get other camera views - cannot view multiple scenes simultaneously 4) Head tracking difficult with time delay
Wide Video Panel	1) Allows for more eye scanning and less head scanning 2) Can actuate switches or control panels easily 3) Can partition screen for multiple camera views and computer control displays, pull down menus, etc.	1) Requires large rectangular mounting surface 2) Lower sense of presence since operator can see their own hands during manipulation
Multiple Video Panels	1) Allows for more eye scanning and less head scanning 2) Can actuate switches or control panels easily 3) Can display multiple camera views and displays simultaneously	1) Requires mounting surface 2) Low sense of presence since small screen display 3) Low sense of presence since operator can see their own hands during manipulation 4) Multiple gaze shifts required to scan all panels for relevant information
HMD & Video Panels	1) Can use HMD for fine manipulation tasks and video panels for all other camera views and control panels	1) Low presence due to switching back and forth 2) Limited field of view

2.7.2 Auditory Displays

In general, alert and warning information is most easily provided by an auditory cue. Auditory cues are detected faster than visual stimuli, and can be received at any orientation of hear, eye or body position. Auditory cues can be given with directional information, leading to the 3D sound technology currently available. However, as with visual overload, auditory clutter can arise if the signals are intrusive, distracting, or lead to a break in concentration. There are two types of auditory displays – speech and non-speech. Non-speech displays, consisting of tones, buzzers, bells, etc., can vary in intensity, duration, frequency (pitch) and location (origin), but are information limited. These types of tones are best suited for alerts or warnings. Types of alerts that a teleoperator may be give include exceeded force/torque limit, exceeded reach/joint limit, exceeded velocity limit, or collision detection/avoidance. It has been shown that subjects can learn to distinguish up to 10 signals, although the meanings are usually forgotten over time.

Speech signals are better suited for complex information, i.e. telling the operator not only that there is a problem, but also what the problem is. Research has shown that visual cues combined with speech cues are preferred over visual combined with non-speech cues. However, speech is a relatively slow way to transfer information, and subjects can usually not discern the intent of the message until close to the end of the transmission. Longer messages would be better suited to the visual modality (either as a separate instrument or a graphical display). Marmolejo developed an HUD in conjunction with voice recognition software for an astronaut EMU giving the user "hands-free" status checking capabilities and suit control. The suit interior provided minimal background noise, reducing the occurrences of incorrect and false alarm voice commands, and required a small 50-word vocabulary. In addition, since each astronaut has his/her on suit, the voice recognition software did not need to be speaker independent.

Speech is becoming an increasingly important capability on Robonaut. The number of systems that must be controlled during a teleoperation session is steadily increasing, and as the operator's hands are typically tracked for robot control, voice is an attractive option for controlling robot systems. In addition, with the visual field of view limitations in the HMDs, the real estate available for visual displays is at a premium. Vocal cuing of operators during tasks is currently under investigation to relieve some of the visual overload, and is incorporated into one display under evaluation in this document.

2.7.3 Tactile Displays

Since it is known *apriori* that the human will be operating under a time delay, there are certain conclusions one can arrive at based on the nature of force feedback in such circumstances. Firstly, the technology that could supply force and torque information to the hand is intrusive to the user. Secondly, reactive force feedback would elicit operator control inputs when none are required, as opposed to supplying passive force information. Rather than reflecting force back to the user's hand or limbs with traditional exoskeleton systems (force reflecting joysticks while popular, are not applicable to Robonaut), vibrotactile stimuli can be used. Stimuli can be varied in frequency, intensity and position on the body to convey static position information, velocity or flow information, as well as force/torque and contact information. Unfortunately, this type of stimuli, while considerably easier to integrate and less cumbersome, is not always of a passive nature. In addition, almost any form of force feedback in the presence of a time delay can lead to operator-induced instabilities –control and command decisions are made based on erroneous (delayed) state information. Passive sensory substitution displays have been shown to increase operator performance in the presence of a time delay, however those can involve the auditory and visual channels.

A comparison of which types of information would be best suited for each modality can be made. Table 2.2 shows a ranking of the information types. Note that although Kinesthesis was mentioned above, it is not included below since that self-motion cue would be provided by a rotating portable foot restraint, such that as the robot turns, the astronaut receives the self-motion cue as well. The rankings are numbered 1-6 with 1 being the most appropriate and 6 the least appropriate.

Table 2.2 Types of feedback appropriate to each modality

Rank	Visual	Tactile	Auditory Non-Speech	Auditory Speech
1	**Position/ Orientation**	**Contact**	**Alert**	Alert
2	Force/Torque	Force/Torque	Proximity	**Force/Torque**
3	Velocity/ Rotational Vel	Alert	Contact	Contact
4	Contact	Proximity	Force/Torque	Proximity
5	Proximity	Velocity/ Rotational Vel.	Velocity/ Rotational Vel	Velocity/ Rotational Vel
6	Alert	Position/ Orientation	Position/ Orientation	Position/ Orientation

Position/Orientation - Overlaid graphical representation of the robot arms or predictive display could be supplied in addition to the video feed to the head-up display.

Force/Torque – Could be provided as a visual instrument display in the periphery to give a quick analog readout of the exerted force levels. To alert that the force/torque has been exceeded, a speech cue would be the most effective.

Contact/Proximity – It is not possible to have a computer model of the layout and specifics of the worksite for every EVA task, therefore unless ranging sensors are added to the Robonaut exterior, proximity and contact information may not be available. If collision avoidance is discernable, a simple auditory tone could be used, or a more complex overlay predictive display.

Velocity/Rotational Velocity – Rotational velocity is essentially provided by the vestibular self-motion cue. Velocity of the robot limbs could be discerned from differentiating the visual signals from the video cameras, or with an analog readout.

2.8 Human-Computer Interaction Design

Gillan [1993] suggests that the primary work of a human factors researcher is to identify the ways a system should display information to the user, and the types of inputs that the user should provide to the system. Czerwinski [1993] explains further the types of questions a human factors engineer should ask. For example,

- What information does the user need?
- What does the user have to do with the data?
- What functions should be allocated to the machine versus the user?

Displayed information could be held constant, requiring the user to search through, integrating and classify the data to form an internal model of the system state. Alternatively, the system, based on its own intelligent diagnosis, could display only relevant information in order to reduce the user's search set. The latter option represents a branch of research closely tied to SA, namely "mode awareness", a problem long held by pilots working in conjunction with automation in cockpit systems. In situations of shared control and automation, operators can be unaware of the mode that the system is operating within, and as a result, can erroneously interpret output information, and likewise make incorrect input actions. Although the Robonaut system will not at the outset rely on automation, there is still the issue of shared control and how the display of information to the operator will be manifested.

There are several groups who have constructed partial dexterous manipulation workstations. The group at Johnson Space Center designing Robonaut has created a full immersion testbed for dexterous manipulation research called the DART/FITT testbed. Preliminary experiments were conducted by the author using DART/FITT, and is described in further detail in Chapter 3. A graduate student at the University of Maryland's Space System's Lab is developing a workstation to operate Ranger, a dexterous free-flying robot. Cannon and Thomas [1997 at the University of Pennsylvania have used a CyberGolve™ to handle virtual tools and is studying shared control modes of operation. They have developed software that enables an operator wearing the CyberGlove™ to position virtual tools on a real video view of a worksite, and then instruct the robot to "put that there". In this supervisory control mode, the operator is not directly telemanipulating the objects, rather they specify the position and orientation of objects. Their robot testbed has been pre-programmed with tool information including mass and handling properties (tool primitives). It then recalls this information for the tool selected, and calculates the trajectory required for task completion. Combining video and graphics requires the computing power of a Silicon Graphics (SGI) workstation and video board. The graphics program constructs the virtual views from the same viewing angles as the cameras at any given instant, therefore the graphics are realistic in size and appearance.

Ranger is a 30 DOF free-flying underwater robot that will be flown on the Space Shuttle to test it's capacity to assist in Space Station construction. Ranger has two 8 DOF arms with modular end effector grippers, one 7 DOF grapple arm and one 7 DOF video arm. Ranger has anthropomorphic arms similar to Robonaut, however it has end effector tools as opposed to a five-fingered hand, therefore the workstation contains no body movement tracking device, only two 3 DOF hand controllers and two 6 DOF mice. The ground control station also employs three SGI O2's, one SGI Octane, four 9" video monitors (for live video), two 17" monitors (for stereo live video). A smaller flight based control station contains an SGI O2, three video displays, a keyboard, two hand controllers, and an instrument panel. The flight control station is afforded one double-locker in the middeck, and three standard lockers.

The DART/FITT testbed was the starting point for the Robonaut workstation design. It's components include a color stereo HMD, microphone and computer speaker sound, two CyberGloves™, Polhemus™ sensors for arm tracking, a rotating chair and four foot pedals to control chair rotation right and left, freezing the arm position and activating voice recognition. There are several immediate drawbacks to the testbed, which make it not suitable for in-flight use. In its current configuration, operation requires two people. One person activates the computer, calibrates the gloves, and controls the "kill" switch, while the second operates the telerobot. In addition, the telerobot the operator is controlling is only a few feet away, therefore the operator can hear the robot moving it's actuators, the interaction of the tools with obstacles, and experiences no time delay. Care should be taken to design a system and trainer that does not give the operator audio cues that will not be available in practice. Finally, the rotation chair discussed previously, is not a feasible piece of hardware to have on board in its current design, although ideally, some type of motion cue could be provided

3 Teleoperation and Robosim

Any sufficiently advanced technology is indistinguishable from magic.
- Arthur C. Clarke (1917 -)

The following chapter describes the methods and hardware associated with Robonaut teleoperation. These devices are primarily off-the-shelf hardware and can be used in a number of remote operations applications. The Robonaut teleoperation system is currently under development, therefore the hardware configuration can be expected to change over time as new technologies and design constraints become a reality.

3.1 Robot Teleoperation

A Robonaut teleoperator wears a variety of virtual reality display and control technology to immerse themselves in the robot's workspace, thereby creating a sense of 'presence' at the robot worksite. The user's body position, tracked by an array of sensors, is sent as a command to the robot brainstem software that in turn generates the robot motions. For the Robonaut system, the teleoperator is seated in a remote location wearing instrumented Virtual Technologies, Inc. (Palo Alto, CA) Cyber Gloves that measure the displacement and bending of the fingers (See Figure 3.1).

Figure 3.1 CyberGlove

A Polhemus FASTRAK® (Colchester, VT) (see Figure 3.2) system measures the position of the subject's hands, head, arms and head relative to a fixed transmitter. The system consists of four receivers (one for the chest and head, and one for each hand), the transmitter, instrumentation unit and power supply.

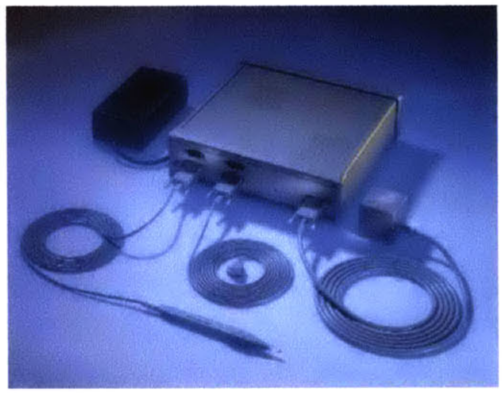


Figure 3.2 Polhemus Fastrak

For these experiments, only the right hand/arm, chest and head sensor is utilized. The hand receiver is attached to the CyberGlove on the back of the palm. The Polhemus is actually measuring the Cartesian coordinate position of the Point of Resolution (POR), or the point in the center of the palm on the back of the hand. The measured POR position is inserted into the Robonaut brainstem inverse kinematics equations that generate the corresponding arm position (joint angles), thus the robot joints are not commanded directly. This method allows Robonaut joint limits to be taken into account during these calculations, such that the position of the robot body is always within the robots' capabilities, work and joint envelopes, and without causing any undue stress on the robot motors and limbs.

The Polhemus electronics unit contains the hardware and software necessary to generate and sense the magnetic fields, compute position and orientation, and interface with the host computer. The receiver is a triad of electromagnetic coils enclosed in a plastic shell that emits the magnetic field, and is the system's reference frame for receiver measurements. The transmitter is a lightweight cube that detects the magnetic fields emitted by the transmitters as they are moved. The position and orientation of the POR is determined relative to the chest coordinate frame (chest receiver). If the operator is in a configuration where he/she is out of human arm reach and decides to lean forward to gain access to the target, the Robonaut torso will likewise lean forward and the robot's arm will remain indexed relative to the chest, rather than to the transmitter as an independent point in space. The chest sensor is indexed to the Transmitter. Figure 3.3 shows a schematic overhead view of the operator seated wearing the teleoperation hardware, and the Polhemus coordinate frames for the right and left hand POR, the chest, head and base (transmitter). This figure illustrates the configuration for the in-laboratory experiments.

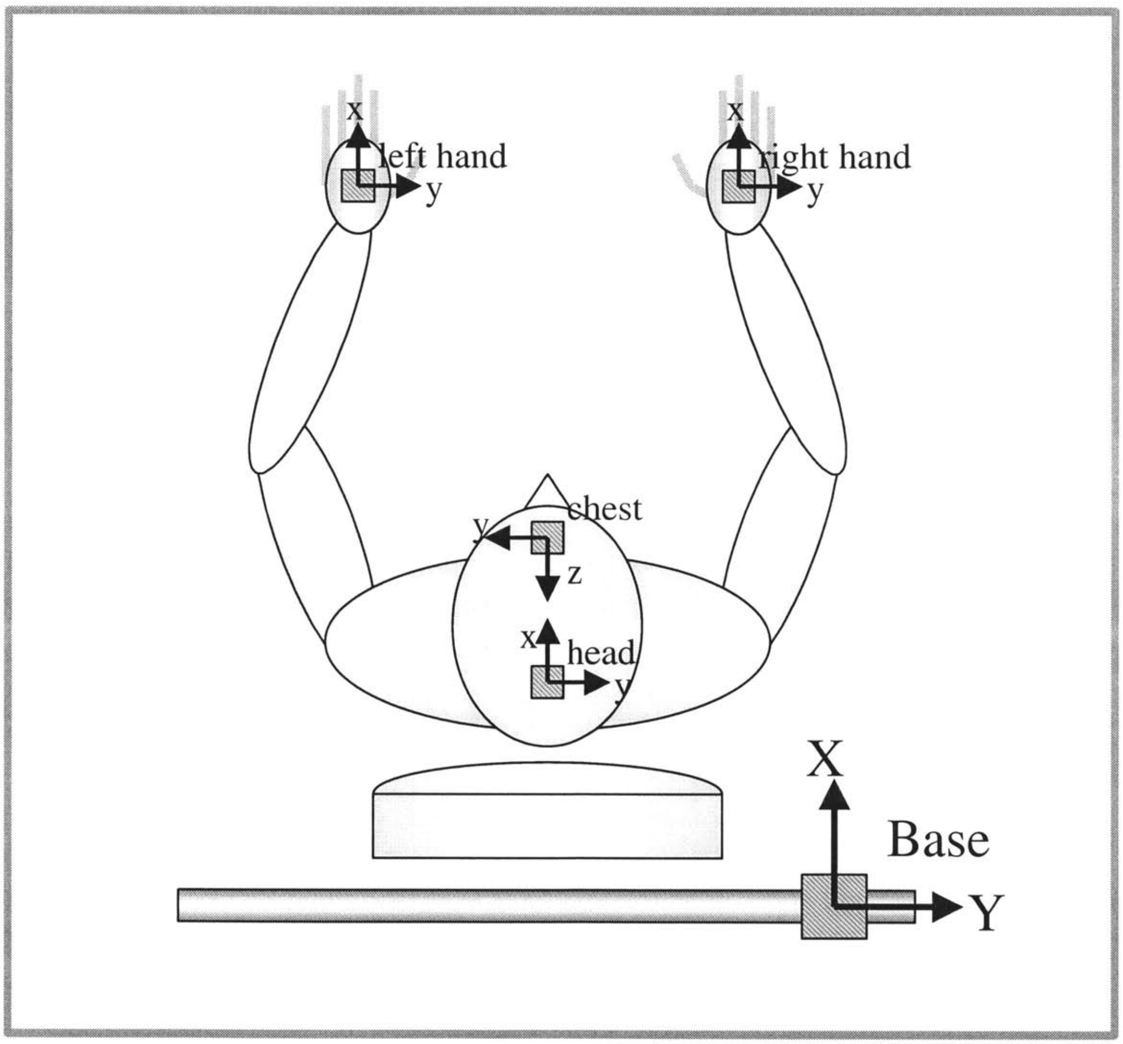


Figure 3.3 Polhemus sensor coordinate frames for in-laboratory experiments (drawing courtesy of Fred Rehnmark, Lockheed Martin, Houston, TX)

The transmitter and receiver must be within approximately 30 inches of one another and measurements may be adversely affected by nearby metal objects. For this reason, a lexan beam with an anodized aluminum mount is used to house the Polhemus transmitter. Figure 4.4 shows a schematic of the support.

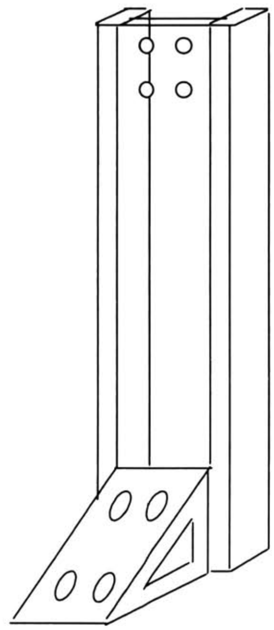


Figure 3.4 Lexan support for the Polhemus transmitter

Robonaut has two cameras for eyes and the live video feed received from them is sent to a Kaiser Electro Optics, Inc. (Carlsbad, CA) ProView 60 helmet-mounted display (HMD) (Figure 3.5). Teleoperators are presented with the stereo view from these Robonaut cameras through this HMD.

Figure 3.5 Kaiser ProView 50 HMD

A transmitter is also mounted on the helmet so that the motions of the user's head are tracked. As the operator moves his/her head to the right or left, the robot likewise turns its head. In this way, the human is meant to feel that they are immersed and present at the robot site doing the tasks themselves. Figure 3.6 shows a subject seated wearing the telepresence hardware.

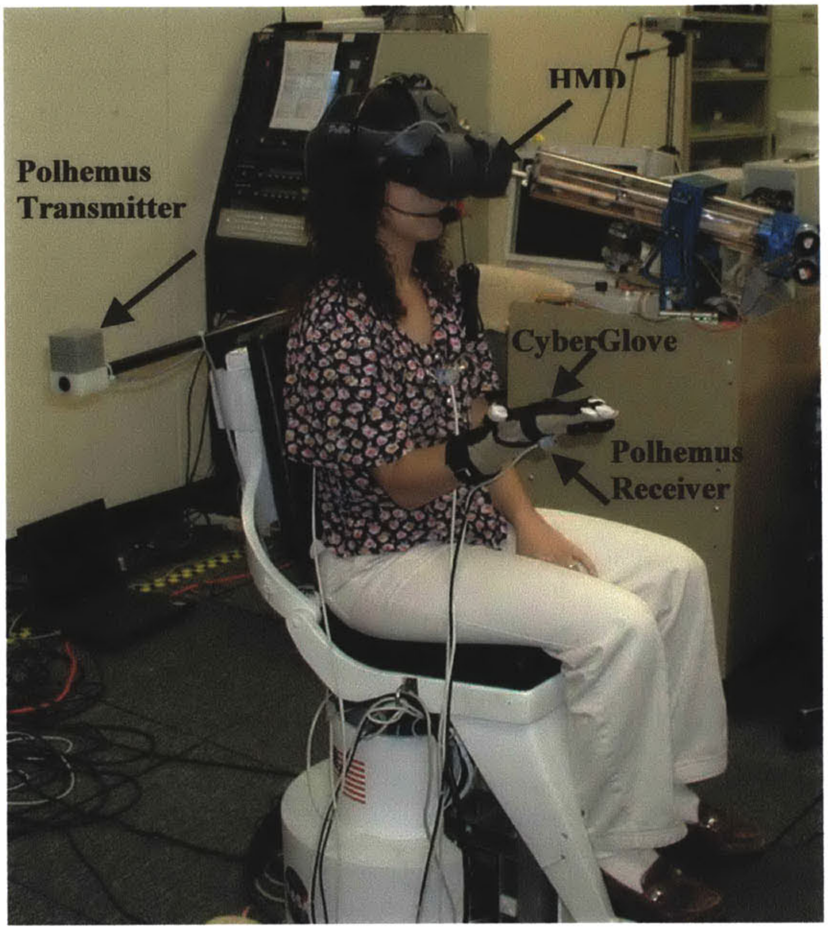


Figure 3.6 Telepresence hardware

3.3 Robonaut Kinematics

The kinematic relationship between adjacent Robonaut joints (connected by a rigid link) is described using the standard Denavit-Hartenberg (DH) notation [Asada and Slotine, 1986; Craig, 1986]. The DH notation requires that a reference frame be attached to each joint. The relationship between two links is then determined from the relative position and orientation between the two coordinate frames. In this case, DH parameters that are determined from Robonaut geometry are used to obtain the coordinate transformations from the POR to the chest frame. The DH notation employs a method whereby a point in the link n coordinate frame is described in terms of the coordinate frame of the (n-1) link. Successive transformations will arrive at a solution such that a point in the end effector frame (n) is written in terms of the 0th frame. In general, the 4x4 matrix T, giving the position and orientation of the end link (n) relative to the base frame (chosen for Robonaut to be the chest) as a function of joint displacements (θ) is:

$$T = A_1^0(\theta_1)A_2^1(\theta_2)...A_n^{n-1}(\theta_n) \qquad \text{(Eqn 3.1)}$$

Where A_i^{i-1} is a 4 x 4 matrix containing the direction cosines of axes of frame i in the first three columns, and the position of the base in the fourth. The physical DH parameters for Robonaut (identical to those used in Robosim) are listed in the Robosim configuration file in Appendix D. Figure 3.9 shows a schematic of Robonaut with the DH coordinate frames labeled. The subscripts in Figure 3.9 refer to the following: W = waist, R = Right, L = Left, H = Head. The frame indices increase outwards from the chest for the arms and head, but not for the "tail". The tail frames are numbered increasing up the torso from "ground". This was done mainly for historical reasons, as the tail was the last segment constructed. Joints one and three on the arms are "roll" joints, whereas joints two and four are "pitch" joints. In the following sections and chapters, joints will commonly be referred to by their anatomical corollaries – for example, joint three would be called the "elbow pitch" joint. As noted in the figure, joint 5, the forearm roll, has a value of θ = +/- 90 degrees (for the right and left hand, respectively). At $\theta = 0$ degrees, the palms will face down. The head is turned –90 degrees in order to better indicate the neck reference frames. All joints rotate about the Z-axis, as is common in robotic systems. Figure 3.10 shows a graphical picture of the robot arms annotated with the directions of positive rotations.

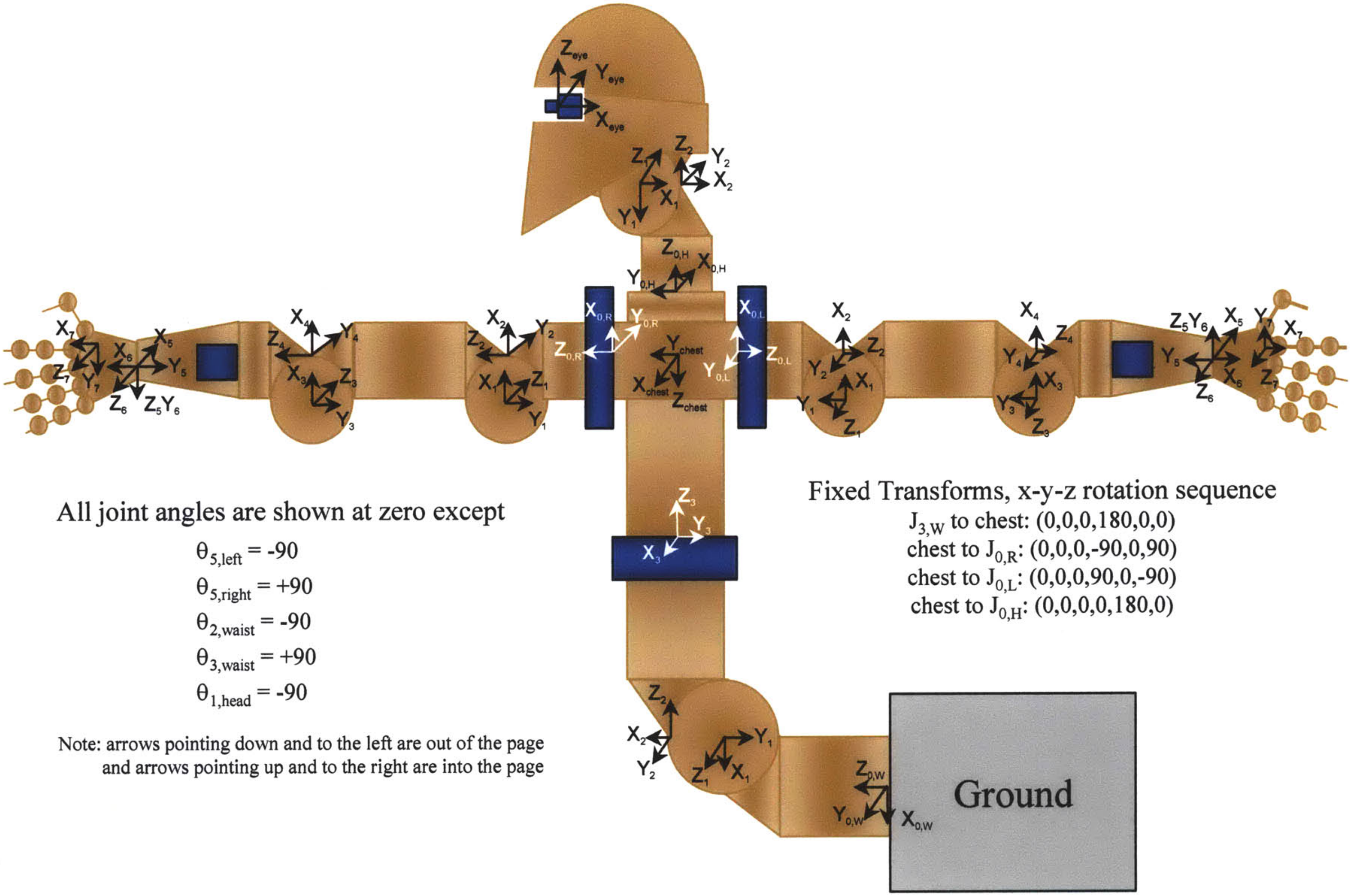


Figure 3.9 Robonaut DH reference frames (courtesy of Robert Ambrose, JSC)

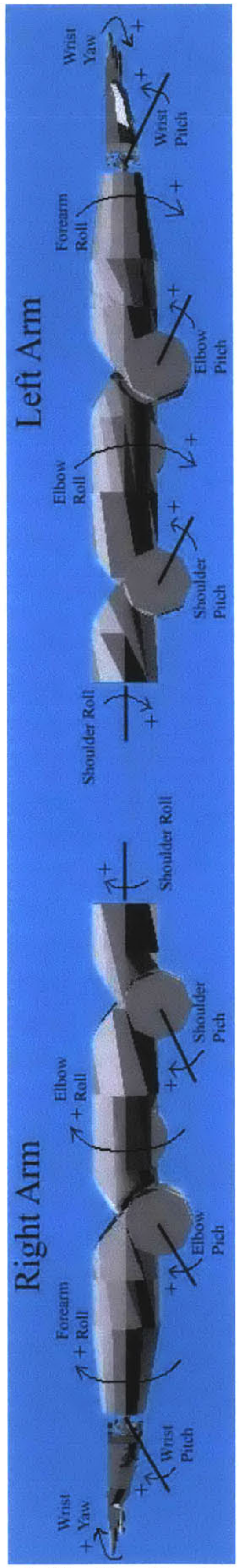


Figure 3.10 Robonaut arms indicating the direction of positive joint rotation

Each arm contains 7 degrees of freedom (dof), 3 dof in the waist and 2 dof in the head, and 12 dof for each hand. Figure 3.9 shows not only the coordinate frames for the joints in the system, but the base frames for each of the segments as well. Using the DH notation, the joints and coordinate frames are listed in Table 3.1 along with their anatomical names. Rows in blue indicate a joint reference frame. Note that the chest frame is the centralized reference frame and is not associated with a physical joint.

Table 3.1 Robonaut joint, coordinate and anatomical names

Joint / Coordinate Frame Name	Anatomical Name
$J0_W$	Tail/Waist base frame
$J1_W$	Tail Roll
$J2_W$	Tail Pitch
$J3_W$	Waist Roll
Chest	Chest Base Frame
$J_{0,R}$	Right Shoulder Roll
$J_{1,R}$	Right Shoulder Pitch
$J_{2,R}$	Right Elbow Roll
$J_{3,R}$	Right Elbow Pitch
$J_{4,R}$	Right Forearm Roll
$J_{5,R}$	Wrist Pitch
$J_{6,R}$	Wrist Yaw
$J_{7,R}$	Right Hand POR
$J_{0,L}$	Left Shoulder Roll
$J_{1,L}$	Left Shoulder Pitch
$J_{2,L}$	Left Elbow Roll
$J_{3,L}$	Left Elbow Pitch
$J_{4,L}$	Left Forearm Roll
$J_{5,L}$	Left Pitch
$J_{6,L}$	Left Yaw
$J_{7,L}$	Left Hand POR
$J_{0,H}$	Head Base Frame
$J_{1,H}$	Head Yaw
$J_{2,H}$	Head Pitch
E_{ye}	Eye Base Frame

3.3 Robonaut Command and Control

Although Robonaut is humanoid in form, controlling the robot arm and hands (as compared to a human), involves some subtle yet important differences. The most distinct difference is that the position of the robot arms (the values of the individual joint angles) is determined from a single command input from the POR. Only the Cartesian position and orientation of the palm drives the arm location. Each human arm joint is *not* directly mapped to a robot arm joint, therefore the operator cannot directly command, for example, shoulder pitch. Instead, the commanded POR position is converted into commanded joint angles by the brainstem. These commanded angles are then filtered by the Robonaut control loop in the brainstem to ensure that no physical system limits are exceeded. If this limit check was not performed, the operator could drive the robot to a state that is harmful to the hardware. This method allows for maximum control over the robot joint outputs and reduces wear and tear on the robot imposed either directly or indirectly by the human operator. The compulsory limits on the robot system include joint angle limits, motor torque limits, Cartesian coordinate limits, and motor rate limits. Figure 4.11 shows a high-level block diagram of the Robonaut control loop.

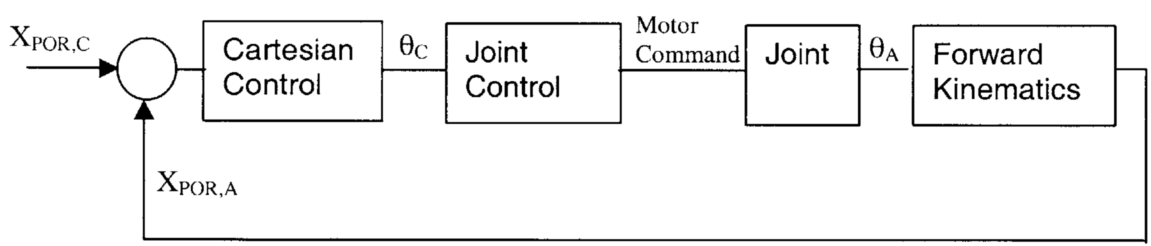


Figure 3.11 High-level Robonaut control loop block diagram

A commanded POR position ($X_{POR,C}$) is input to the system. First, the inverse kinematics calculations yield the commanded joint angles (θ_C) and Cartesian limits are imposed. Commanded angles are input to a second filter where rate, angle and torque limits are applied. Subsequently, a motor command is generated and the actual joint angles (θ_A) resulting from the motor commands are measured through the encoders.

Finally, the measured angles are input to the forward kinematic equations and the calculated actual POR position ($X_{POR, A}$) is fed back into the system.

In its current incarnation, the Robonaut limits are apparent to the operator only indirectly. Operators may feel that the robot is not "going where it's being told". Here, the operator is most likely commanding Robonaut to a position that is outside one of its joint limits. The robot will always try to drive the joints away from joint limits, hence the discrepancy. Likewise, if the robot arm movement "lags" behind the human command, this is an indication that the operator has input a rate that is too high. Some of the limits that are imposed in the laboratory environment, such as the torque limit, may be altered and/or reduced in the microgravity environment. With the motors supporting the 1-G weight of the robot limbs, the controller helps to keep the arm in a configuration that minimizes the amount of torque on the motors. In the microgravity environment where inertia is the dominant factor rather than weight, these limits are likely to be lowered. As a result, the work envelope of the robot will increase. Finally, there is a rate limit on the robot that prevents the robot from moving beyond a certain speed. There are two safety reasons for this limitation. First, if the robot moves at a slow rate, the robot can be deemed man-rated, and humans are allowed to enter its workspace and interact with it while powered. This is critical if Robonaut is to be used as an astronaut assistant. Second, there is a desire to filter out fast commands from the operators in the event that they command the robot into a harmful configuration, thorough a dangerous path, or into contact with an un-intended object. The harmful configurations are classified as external limits.

There are three external limits in addition to the internal limits that the Robonaut engineers impose on the operator. Operators are instructed to avoid "chicken winging", self-collision, and excessive wrist pitch. Chicken winging refers to a position where the elbow is high relative to the waist, in a position where the shoulder motors are highly stressed (see Figure 3.12). Self-collision occurs when any part of the robot body is in danger of striking another part of the body. This most often is a result of the operator driving the elbow in close proximity to the waist. The wrist pitch angle is important as its range of motion is limited and a wrist pitch joint limit can be reached with relatively little effort. Once this limit has been reached, the rest of the robot arm is still trying to reach the commanded POR, putting stress not only on the wrist, but on the entire arm as well.

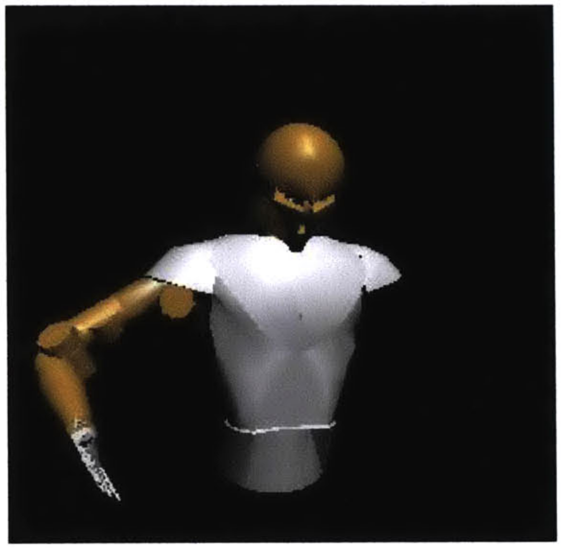


Figure 3.12 Graphic of "chicken wing" robot pose

Robonaut is not currently equipped with collision and proximity sensors and therefore cannot self-monitor a collision condition. This sensor suite is expected to be on-line within the next fiscal year. In terms of monitoring excessive elbow height, creating an internal control loop to monitor and act if necessary could create confusion for an operator if they are not aware that the robot is under a self-command and correct mode rather than a direct tracking mode. In addition this phenomenon is a purely 1-G limit and is not expected to be present in the future microgravity operational environment. Operators are therefore required to perform a secondary task of avoiding these three external limitations. The robot is never operated without and engineer monitoring the session and often times, the engineer will alert the operator if there is the danger of one of these conditions occurring.

A second distinction between humanoid robot teleoperation and human limb control is anatomical mapping. Any operator must have his/her body mapped onto the robot. As the dimensions of the human operators vary, so does the quality of the mapping.

Mapping the hand is one area in which this is prevalent. The human hand contains 27 dof compared to the 12 in the Robonaut hand [1]. The mapping between the two is complicated by the CyberGlove, which commands finger position. The CyberGlove is instrumented with 18 strain gauge sensors. These 18 gauges are reading the complicated finger positions and translating that into command signals for 12 joints. A good calibration is key to a successful mapping between the human hand and the Robonaut hand. To calibrate the hand, the operator places the hand in a series of positions (flat hand fingers together, flat hand fingers apart, fist with the thumb both inside and out) to take into account the size of the hand, range of motion and glove fit.

There is a corollary to the hand calibration that is used to map the rest of the human body to Robonaut. The operator is able to freeze and thaw the robot in order to re-index his/her body to better match that of the robot. This freeze/thaw (F/T) mechanism also allows the operator to rest a limb if it is not in use, and to relax his/her body in between tasks. Freezing the robot, as its name implies, stops the robot from tracking the Polhemus inputs and holds at the last commanded position. Thawing the robot resumes tracking of the human body. A voice command controls the operation and the robot confers the command using the IBM ViaVoice software (White Plains, NY). As a sample, the following is the protocol for freezing/thawing the right arm:

Operator Command: "Freeze Right Arm"
Robonaut Response: "Right Arm Frozen"

Operator Command: "Thaw Right Arm"
Robonaut Response: "Right Arm Thawed"

Re-indexing the body is one of the most frequently performed operations by Robonaut users. Since Robonaut has a greater reach than most humans (due to its increased arm length), it is common for the human to run out of human arm length before reaching a target, while Robonaut will still have reach available. In this case, if the human arm is fully extended, the robot is frozen, the human arm retracted so that they may continue moving forward, and the robot thawed. Re-indexing can also be a useful tool to enhance task performance. If the operator knows that the task will involve moving the arms in towards the body, they may index themselves with their arms extended a bit so that they have room to move inwards and better perform the task. If the operator is in a position where they are supporting the weight of their human arm for some time, they may choose to re-index and bring the human arm into a more comfortable position.

3.4 Introduction to Robosim

The simulation was created for a number of reasons including assisting Robonaut operator training, telepresence workstation design and to act as a robot control testbed. The latter function is for testing of new control algorithms before applying them directly to the hardware. Likewise, other investigators can take advantage of testing their research ideas on the simulation platform before being approved for robot hardware testing. As a design testbed for telepresence, displays, aids and other situation awareness configurations can be ironed out in the simulation modality. Finally, it is desired to integrate simulation training into the path for training Robonaut operators. If operators can learn the workings of the robot and feel comfortable utilizing it via Robosim, it is likely their learning curve will reach steady state more quickly once the robot training begins. This hypothesis will be tested with the experiments described herein.

Robosim (See Figure 3. 7) is under development at the JSC Dexterous Robotics Lab. It uses the Interactive Graphics, Operations and Analysis laboratory (IGOAL) Enigma modeling software (Houston, TX) to create the robot models, environment conditions and camera view, and Real Time Innovations, Inc. (RTI) Network Data Delivery Service (NDDS) software for developing the necessary communication networks and protocols. Robosim is designed to act in several capacities including a control and telepresence display testbed, and eventually as an astronaut training aid.

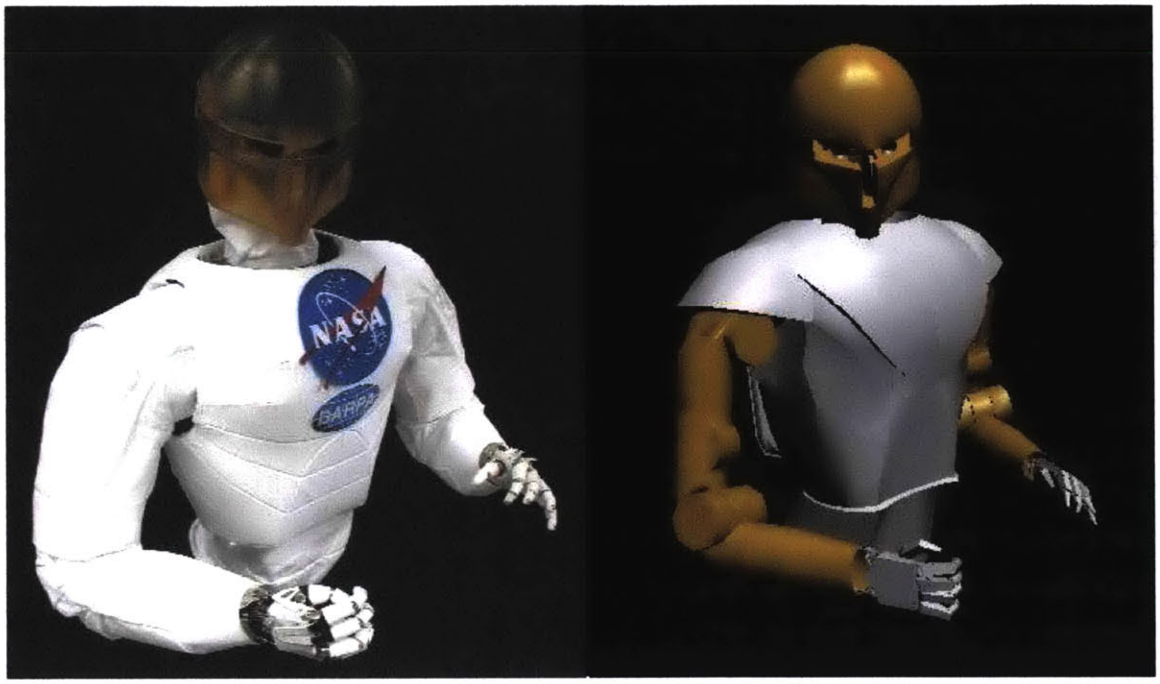


Figure 3.7 Robonaut and Robosim graphic

The Robonaut graphical model was constructed prior to this research effort by the IGOAL laboratory from Robonaut engineering drawings. The graphics were configured to the appropriate environment variables, kinematic transforms, task layout and parameters in Enigma by the author (Jennifer L. Rochlis) and the simulation programmed by Mr. S. Michael Goza using the Enigma files. Code that is required to interface with the simulation package was programmed by the author. This code controlls the display graphics, display functions, drawing routines, operational limits (described in the following sections) and data collection unique to this experiment, as the simulation is written for a general audience.

Robosim employs the identical forward and inverse kinematics as the Robonaut brainstem, therefore given the same command signal, the resultant motion of the simulated robot will match that of the Robonaut. Currently, the simulation is limited in that it does not model contact forces, therefore is not possible to study grasping and tool handling tasks. The simulation, like the robot, is dynamic and therefore can be upgraded in conjunction with the robot hardware and software.

Two Dell Latitude C600 laptops generate the 3-D Robosim views of the robot arms and task panels. Recall that Robonaut has two cameras, one for each eye, which together provide stereo vision to the operator. To generate stereo vision with an HMD using Robosim, it is necessary to generate two different graphical views of the same scene separated by the same interoccular spacing as the Robonaut cameras. The two independent eye views are sent to the HMD as right and left eye inputs. A computer with the capability to send different parts of the monitor to different outputs (such as a Silicon Graphics workstation) would be able to generate both views on the same unit. PC computers are capable of only one VGA output, or the same VGA output signal split to multiple serial lines, hence one computer is needed for each scene view. Figure 3.8 shows the view from one eye that the subject sees in the HMD. Note that the HMD view generated through the simulation has the identical 60degree diagonal field of view as the Robonaut cameras.

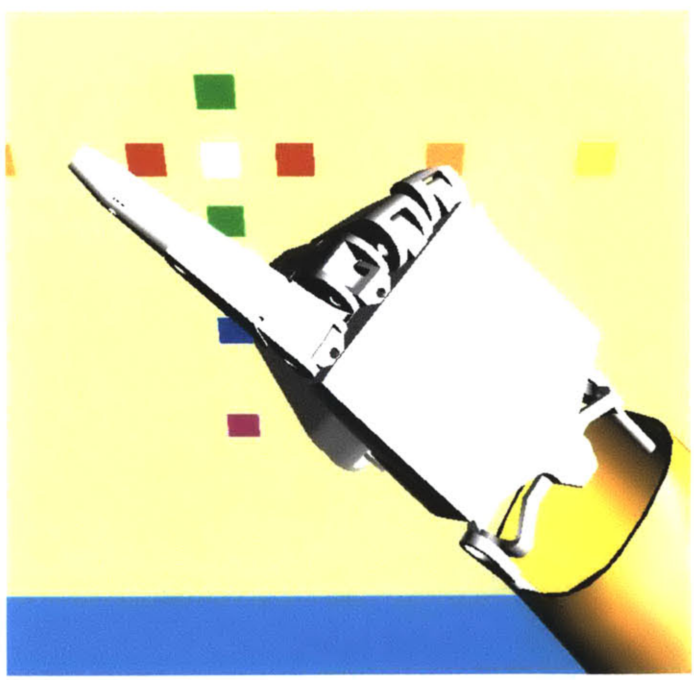


Figure 3.8 View of right eye through HMD of Robosim

3.5 Robosim Command and Control

Robosim is controlled in much the same manner as Robonaut. The primary difference between the two is that to date, contact forces are not being modeled in the simulation. Therefore, the study of grasping is not possible. The lack of contact force modeling renders the Robonaut torque limit useless, as torque is not a variable. Robosim contains the same joint limits and rate limits as Robonaut, but is not limited by Cartesian limits. Safety was the number one reason these limits were initially imposed on Robonaut. A precedence was set as the robot was in its early developmental stages to restrain the allowable movement and gradually learn the capabilities and limitations of the hardware. Currently, the Cartesian limits are almost maximally expanded, however the desire to keep the operator working in a reasonable volume is maintained. Performance differences between the robot and the simulation may differ since the simulation lacks these limits. It is hypothesized that they will not lead to objective performance differences as much as subjective differences. Without the Cartesian and torque limits, the simulation robot arm can "run away" from the operator, and enter a pose that is not possible on the robot, and difficult to recover from. The rate limits on both systems ensures that the operators learn to keep their inputs to a nominal speed to avoid tracking lags and minimize commanded and actual position mismatch.

Robosim command signals are handled through a control loop analogous to the Robonaut control loop. For both the robot and the simulation, data packets are generated by the Polhemus and CyberGlove and sent via NDDS to either the Robonaut brainstem or the simulation control software. In this experimental configuration (shown in Figure 3.13) the simulation runs in "command" mode on one laptop computer (where the right eye view generated), and in "listen mode" on a second laptop.

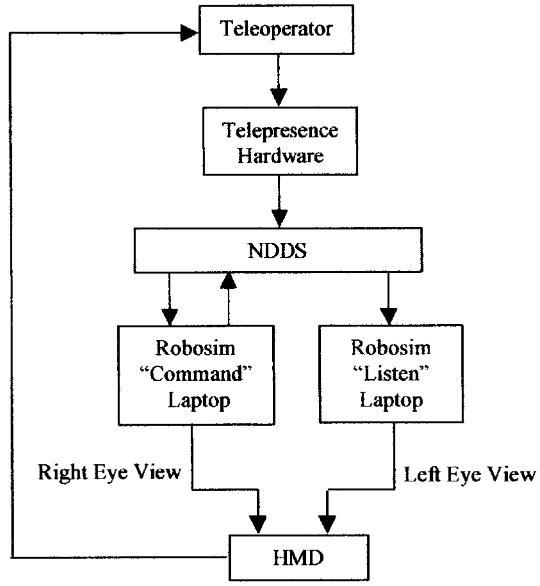


Figure 3.13 Schematic block diagram of the Robosim data flow

In command mode, the simulation listens over NDDS for a commanded data packet (shown in green in Figure 3.13) sent from the teleoperation hardware. It then runs the commanded data through its internal control loop and publishes a new data packet with the actual angles (shown in blue in Figure 3.13). This simulation listens over NDDS for the actual angle data packet and updates the Robonaut graphical model from there. Therefore the simulation software is set to listen only to specific types of data packets. NDDS allows users to "tag" the data packet with a name that specifies its contents. In this instance, commanded and actual angles are tagged separately. One reason for distinguishing the function of each laptop in this way is to reduce the amount of redundant computing power required to run Robosim. It is unnecessary to have an independent control loop operating on each machine. Each running simulation utilizes a large amount of Central Processing Unit memory, therefore the simulation and various supporting software programs are divided between the computers to ensure proper update rates, and avoid overloading the system. Another benefit of this system is that as long as terminals are connected to the internet, the simulation can be running on one machine and broadcast to multiple listeners needing only the graphics program to function. Figure 3.14 compares the data paths for Robonaut and the simulation as configured for the experiments described herein. The data form the HMD is sent to a VCR for data collection purposes offering a view of what the subject is looking at throughout the task. The Robonaut data packet is sent to a PC also as collected data. As the simulation runs on a PC, it automatically saves the data packet information whereas the Robonaut data stream must be recorded externally.

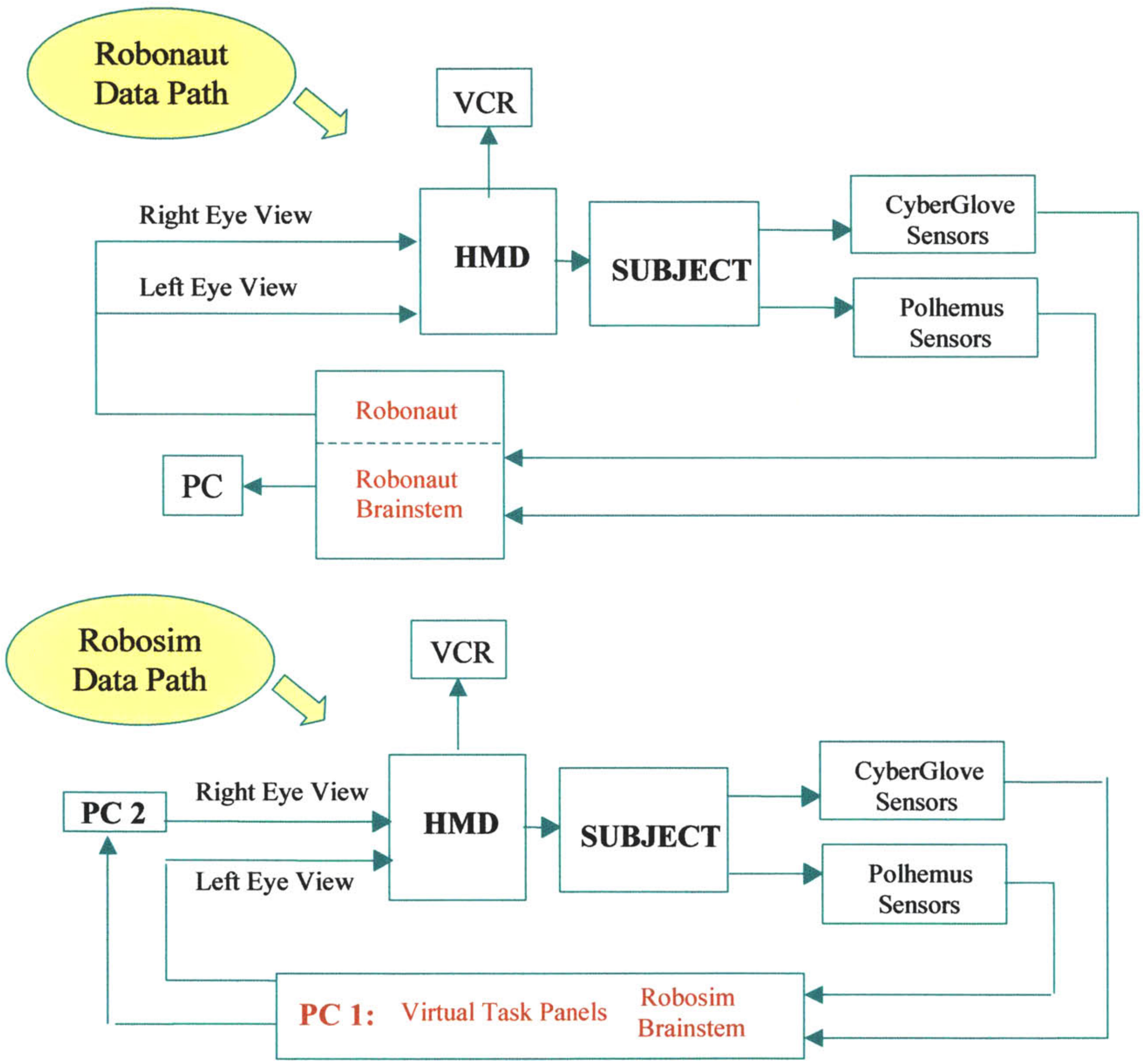


Figure 3.14 Data path comparison between Robosim and Robonaut

For Robonaut, the command data is sent to the robot where the brainstem calculates the actual angles and moves Robonaut to that position, which the subject then sees. For the simulation, one PC receives the command packet from the sensors, calculates and updates the position of the Robosim graphic with actual angles. This PC also generates the Left-eye view. The actual angles are sent to a second PC that simply listens to the data from PC1, updates the graphics and sends this out as visual data to the right eye of the HMD.

3.6 Robosim Graphics

The simulation is essentially a Visual C++ that interfaces with Enigma model code, NDDS and any other supporting software. The Robonaut graphics used by the simulation are a series of geometrical models generated in the Enigma program. All model and environment information is stored in a structure file. Structure files contain a series of model nodes organized into a hierarchy that call upon model geometry files. The Enigma software is the graphical interface tool used to create both the model geometries and the structure files. For Robosim, engineering models of each Robonaut segment were converted into Enigma models. These models were assembled using the graphical interface to form the robot graphic as a whole, with segments linked appropriately. For example, every segment of the arm is linked the previous segment so that when the Robonaut shoulder moves, the rest of the arm moves along with it. This relationship is called parent-child. The shoulder in this case would be the parent with the upper arm, elbow, forearm, hand and fingers being the children. Likewise, the shoulder is a child of the Robonaut torso so that torso movements lead to appropriate arm movements, and so on. The diagram representing these relationships is called a "tree display", shown in Figure 3.14.

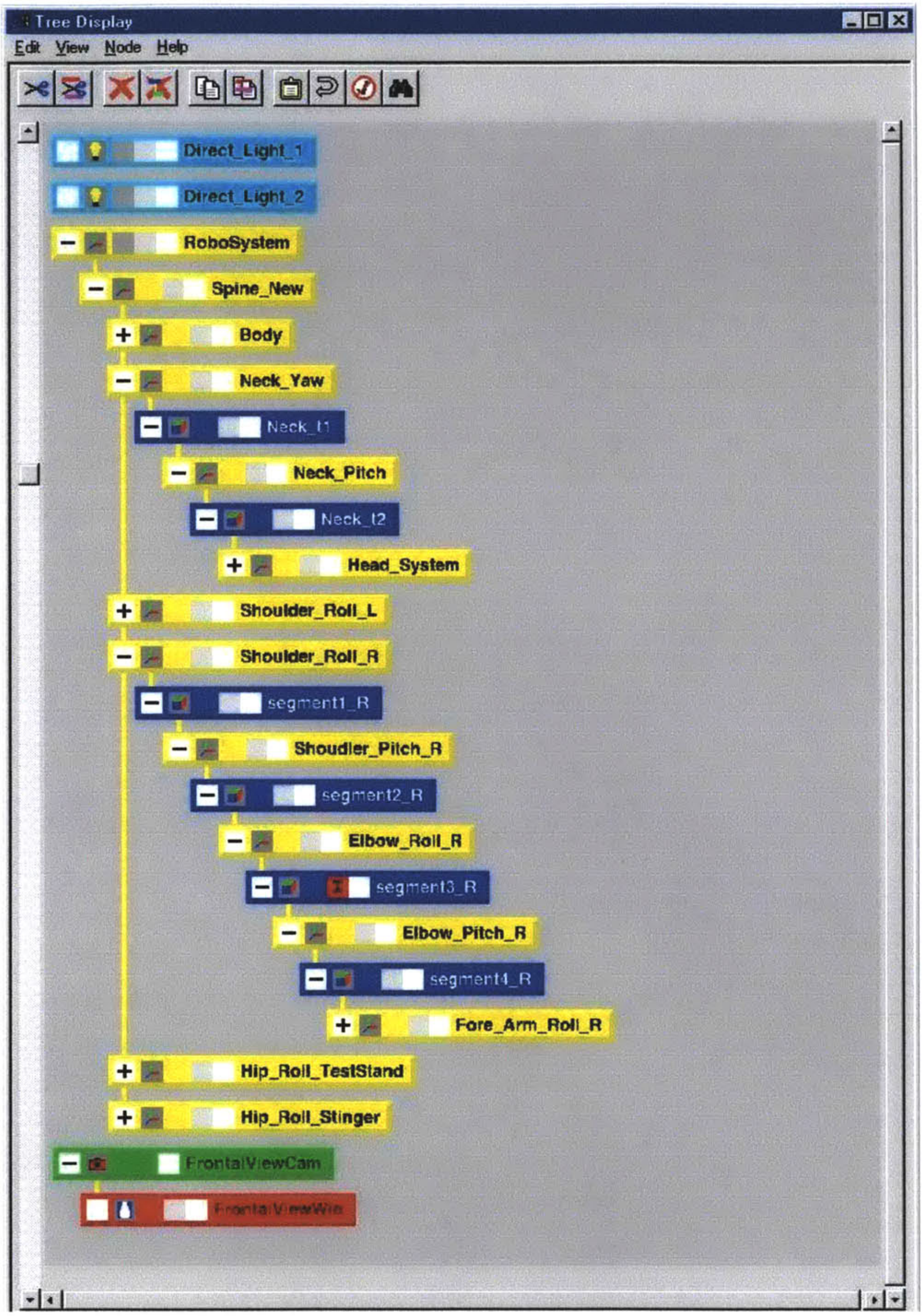


Figure 3.14 Enigma tree display window

The yellow boxes are system nodes that may have "branches" within. Blue nodes are model nodes where the individual segment information is contained. Notice that the Fore_Arm_Roll_R system node towards the bottom of the window has a "+" in the left-most box. This indicates that it is not expanded. Expanded nodes have a "-" in the box indicating there are no further children. The Shoulder Roll left and right nodes are the robot arms and they are linked along with the neck and body to the Robonaut spine. Green nodes denote cameras and red nodes the viewing windows. Segment 3_R has a red I mark denoting that this model visibility is turned off. Figure 3.15 shows the model that this tree diagram represents and you will note that one of the right arm segments is not drawn.

Figure 3.15 View of Robonaut model shown in tree display

Finally, clicking on one of the nodes in the tree brings up the dialog box shown in Figure 3.16. Here is where the position and orientation data for each model is located. Notice at the bottom that any parent nodes for the active model are listed.

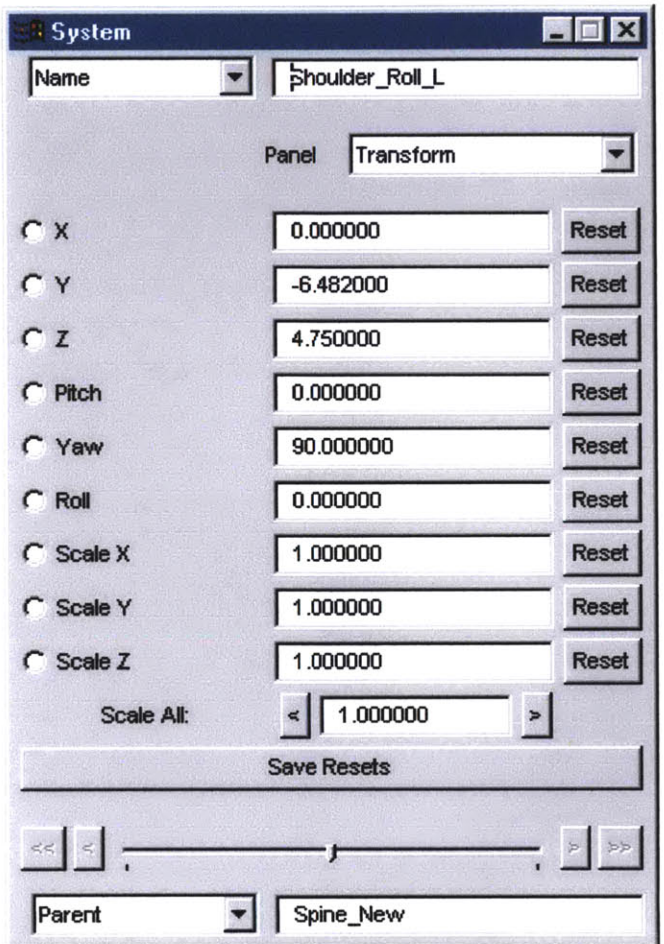


Figure 3.16 System node dialog box

Numerous other parameters and features are available within Enigma but will not be discussed in detail. The structure file will also contain any models that you want in the robot environment. The virtual task panels are drawn using Enigma and linked to the robot and the robot's reference frame within this structure file. Therefore the structure file contains all of the environment data for your simulation including the colors, lighting, camera angles, task panels and positions and orientations of the models. Finally, the structure file generated by Enigma is a text file that can be altered through a text editor or the graphical interface. A sample of the structure file is listed in Appendix D.

4 Movement Classifications and the Display Design Paradigm

If we are to achieve results never before accomplished, we must expect to employ methods never before attempted
- Francis Bacon

In this chapter, the focus turns to the iterative design approach to be used for the telerobotic displays. First, a classification is introduced that will set the framework for the research experiments. Next, the experiments will be described in detail in the context of the design process described in this chapter. These experiments will verify the proposed classification, transitions-based roadblocks and the simulation-Robonaut performance transfer.

4.1 Basis Movements

One of the goals of this research is to understand full-immersion teleoperation of EVA tasks from an integrated task perspective. However, before investigating integrated EVA tasks, it is important to understand the "building blocks" or individual elements that an EVA task is comprised of. This will allow experimenters to determine an operator's baseline teleoperation performance characteristics, as well as understand the fundamental components of the EVA suite of operations.

The following sections describe the task terminology introduced as a result of this thesis effort. An extensive study of EVA activities was conducted including exploration of

EVA tools, interfaces and procedures, and EVA flight tasks underwater training and timelines from previously flown Space Shuttle missions. As a result of this assessment, a classification of EVA movements was determined.

Every movement carried out by an astronaut conducting an EVA can be defined as one of three movements: fine position movements, gross position movements, and grasping/releasing. These movements have been termed "basis" movements. The basis movements are distinguished from one another in that they each require different mental processes from the operator. Likewise, they require different types and scopes of sensory feedback. The envelopes of these movements are based on observations and study of EVA operations. An EVA task is composed of basis movements and contextual information. It is hypothesized that this contextual information leads to decreases in operator performance. The transitions that occur between basis movements need to be investigated and understood such that displays can be designed that focus on these transition-related roadblocks. As stated previously, display design focusing only on the basis movements may not be the correct solution for the larger contextual EVA task.

The following sections describe each of these basis movements, the transition mentioned above and the display design paradigm in more detail.

4.1.1 Grasping

Grasping refers to the acquisition of an object through contact with the hand, and for the purposes of this document also refers to releasing an object. For Robonaut, it requires fine motor coordination of the hand in, at present, 12 DOF. Since the human arm is redundant, there are an infinite number of arm positions that can lead to the same end effector, or hand position. Likewise, the grip chosen to acquire the object may vary from person to person; therefore there is no unique grasping solution. There may be solutions or grasps that are more desired than others from a stability and controllability standpoint, however knowing which grip is optimal requires knowledge of the objects' handling qualities *a priori*. It is reasonable to expect that astronauts operating Robonaut will be sufficiently trained in all handling qualities of the tools they will utilize.

4.1.2 Positioning

Positioning involves displacing the arm from an initial location to another desired location through a series of torso, shoulder, elbow and wrist joint translations and rotations. The hand may or may not be in possession of an object during this arm movement. A distinction can be made between gross movements (such as reaching for a remote object) and fine movements (such as aligning, adjusting and inserting objects in real-time).

Fine positioning is involved in many tasks including tracking, peg-in-hole and target acquisition. Typically for these motions, the arm joints will sweep through less than 20 degrees (at arm's length). The reduced depth perception resulting from head mounted displays (HMDs) employed in telerobotic operations, degrades the performance of fine position tasks. A reduction or absence of force feedback (as experienced by astronauts wearing EVA gloves, and by Robonaut operators) can also degrade fine positioning performance. During fine position motions the operator narrows his/her concentration to a precision-level tasks. If the operator becomes too intent on the fine positioning at hand (often due to a difficult or high-workload task), external hazards may go undetected.

Gross positioning involves larger motions (greater than a 20 degree sweep through the joint angle at arm's length) generally associated with transporting objects from one location to another, reaching for objects, and turning or translating within the worksite. With the field of view limitations of the current HMDs (approximately 65 degrees) and EVA helmets, collision avoidance and Situation Awareness of body position within the environment become important factors during gross position movements. Gross position movements are often bounded on either side by fine position motions and the transition from one to another may be complicated by the presence of an object in grasp.

4.1.3 Transitions

Previous work has shown that each of the basis tasks have different optimal displays associated with them. Thus, in order to achieve the best performance during an integrated task, one would need multiple displays. More displays lead to increased amounts of operator workload and number of operator errors. In addition, this linear sum of displays may not be the correct solution for the integrated task.

Operators can perform repeated basis movements independently (grasping a tool, aligning the arm, and translating the arm), or in combination within a larger EVA task (grabbing a tool, bringing it to a toolbox and inserting it). Adding contextual information to a task requires the operator to make methodology decisions about their movements, and may affect subtask performance in a way that cannot be predicted by studying them exclusively. For example, given that a tool is to be subsequently inserted into a slot, the operator must decide not only the best way to grab the tool given its subsequent insertion, but they must maintain awareness of their environment while the tool is transported. Alternatively, given the task of simply grabbing a tool, the operator may not determine the type of grasp to be an important factor, only that they need *a* grasp on the tool. This type of contextual information will ultimately increase task times when these transitions between basis movements are introduced, and bring attention to problem areas for the operator (decreased SA, higher workload, etc.) not previously seen during individual subtask tests. Looking at task times for individual basis movements, versus integrated contextual tasks, is essentially asking - is the sum of the task parts equal to the whole of the integrated task? If not, what are the limitations of the system? What display and feedback mechanisms can be provided to increase operator SA and performance and decrease the number of problem areas? Finally, what is the maximum performance that we can achieve? By comparing the parts to the whole, you isolate the transitions that occur between basis movements. Roadblocks that arise when the task is integrated are now apparent, and can be correlated with subjective ratings. Workstation display components can be designed address those problem areas identified by both the objective and subjective performance ratings.

4.2 Display Design Paradigm

The experimental methodology developed in this thesis has been designed to both a) isolate the effects of interest and b) minimize the effect of confounding variables. To this end, both basis and integrated tasks are studied and the experimental methods refined through an iterative design process (see Figure 4.1). Throughout this thesis, the design loop described below will be carried out three times, each time building on the experience from the previous efforts. Figure 4.1 shows a schematic of the display design process. The steps are enumerated as follows:

1) Identify System Issues
2) Develop System Requirements
3) Synthesize requirements into a display design
4) Evaluate the display and reveal design implications
5) Iterate on the process while incorporating newly identified system issues

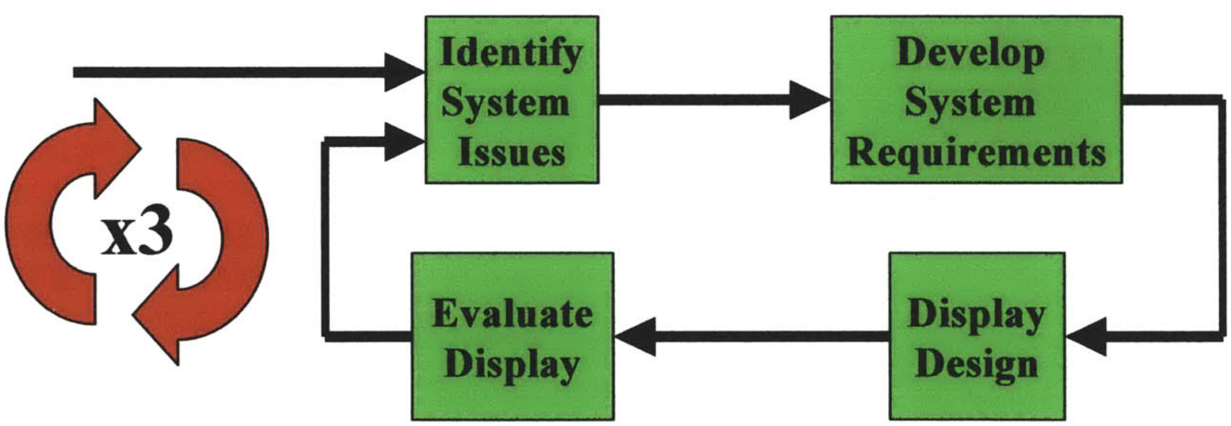


Figure 4.1 Display design paradigm flow chart

The loops through the system begin with exploratory studies using Robonaut predecessor hardware, and include testing both basis and integrated tasks using Robonaut and the Robosim. The first iteration actually involves two experiments. They are both necessary to determine the system issues that will be iterated upon in the subsequent experiments. The three iterations are listed as follows:

Iteration I

- Verify EVA classification basis tasks in practice and that the transitions between basis tasks cause performance detriments by performing integrated task testing

Iteration II

- Test display solution incorporating lessons learned with integrated tasks

Iteration III

- Utilize simulation to re-design and evaluate new display design with integrated tasks

These iterations are presented in sequential chapters. At the start of each cycle, the system issues and requirements are identified. The display solution is presented next based on these requirements. One experiment is conducted between the first and second design iterations. This experiment tests basis tasks and is designed to confirm that the Robonaut and Robosim yield the same operator performance, displays are not under test here. The results of this verification test do however, contribute to the systems issues necessary for the second iteration through the display design process. Once the displays are evaluated experimentally, their design implications are discussed before proceeding onto the next cycle.

5 Display Design Iteration I

All life is an experiment. The more experiments you make the better.
-Ralph Waldo Emerson

On the first pass through the design cycle an integrated task pilot test with an initial display design was tested on to verify the presence of basis movements and performance detriments due to transitions. In an effort to gain an understanding of the system issues involved with subject performance during full-length telerobotic EVA tasks, exploratory experiments were performed at JSC on the Dexterous Anthropomorphic Robotic Testbed (DART), the predecessor of was that its construction was not yet completed. DART is similar in design and complexity to Robonaut, however its technology is not as advanced, and its dimensions are larger than that of a suited crewmember. DART consists of two larger robotic arms with 7 DOF each, plus two 3-fingered hands useful for simple tool grips. DART's two eye cameras provided subjects with stereo vision through a helmet-mounted display (HMD). The subjects' motions were tracked by CyberGloves™ worn on the hands and by the Polhemus™ sensors on the wrists (see Figure 5.1). Both arms and hands were in use during these experiments. Rotations of the DART waist about the base was accomplished using a foot pedal at the base of the subject chair, one for right turns and a second for left turns. The tasks included large scale rotations of the DART body in addition to local fine position tasks.

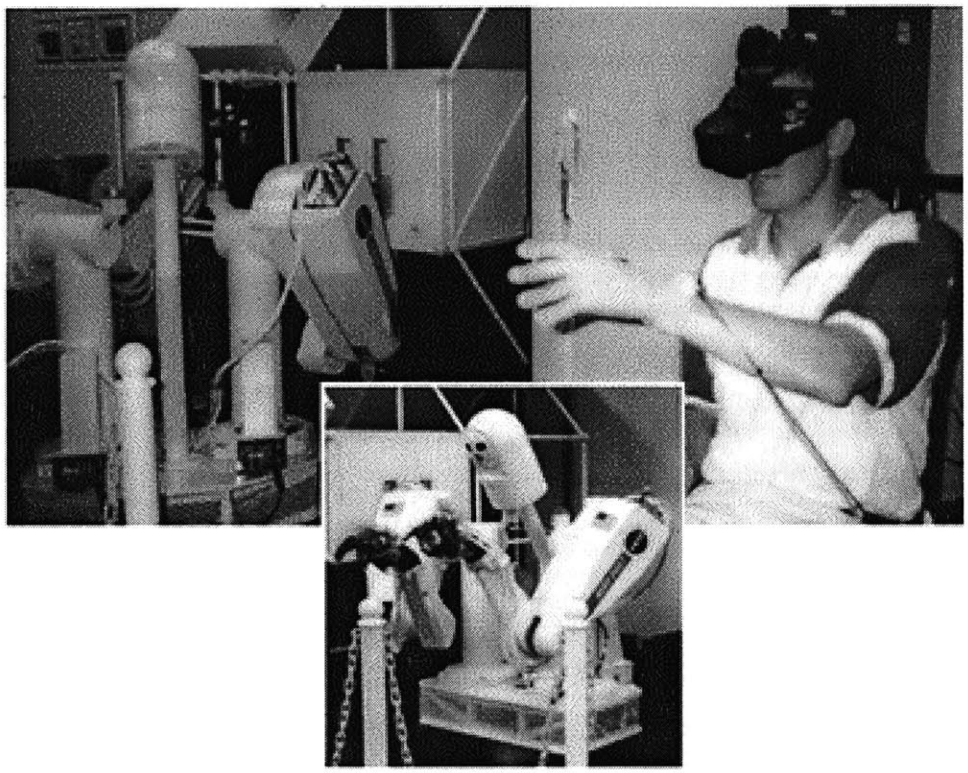


Figure 5.1 Subject performing telerobotic experiment using DART

Four experienced DART operators performed two modified EVA tasks over two trial days: an Orbital Replacement Unit (ORU) changeout, and a tool exchange (the tasks are listed in detail in Appendix F – Pilot Study Task). These two tasks were chosen such that the performance times were similar in length, but the content, difficulty and workload were different. The two tasks required the subjects to perform operations such as tool grasping and manipulation, rotating the robot about its base, opening and closing hinged and sliding doors, target acquisition, tool alignment, manipulating pins and latches, and tool stow and un-stow maneuvers. Video data was taken during the trials and DART joint angle data from the base, shoulders, elbows, and wrists were recorded (data are listed in Appendix G – Pilot Study Data). A subjective questionnaire was administered after the last trial day.

5.1 System Issues and Requirements

A candidate display was tested during these trials. As this was the first telerobotic experiment performed in the series, there were several goals. The first goal was to verify that the transitions between basis movements led to performance detriments as was hypothesized earlier. Second was to identify general Teleoperation system issues. Prior to these tests, the primary system concern was collision of the robot with objects in the robot's immediate environment. In order to avoid singularities and comply with the reach envelope of the DART, the task hardware was placed very near to the robot. DART's arms are much greater in scale than the subject's human arms, and combined with the proximity of the hardware, the opportunity for collisions was greatly increased. As a result, the main requirement for the display was that it provide the operator with a collision avoidance warning. Additional requirements included several human factors concerns namely:

Intuitive interpretation of display information
Multiple warning levels for corrective actions

The DART engineers required that the display be active for all trials, therefore the display was not tested as a variable, however, subjective comments regarding the display were recorded in addition to task time data.

5.2 DART Display

The collision avoidance display was fabricated using the Enigma software program. Once the hardware was placed in the robot workspace, careful measurements were obtained and used to construct a graphical model of the entire workspace. Figure 5.2 shows the Enigma view of the DART arms and workspace.

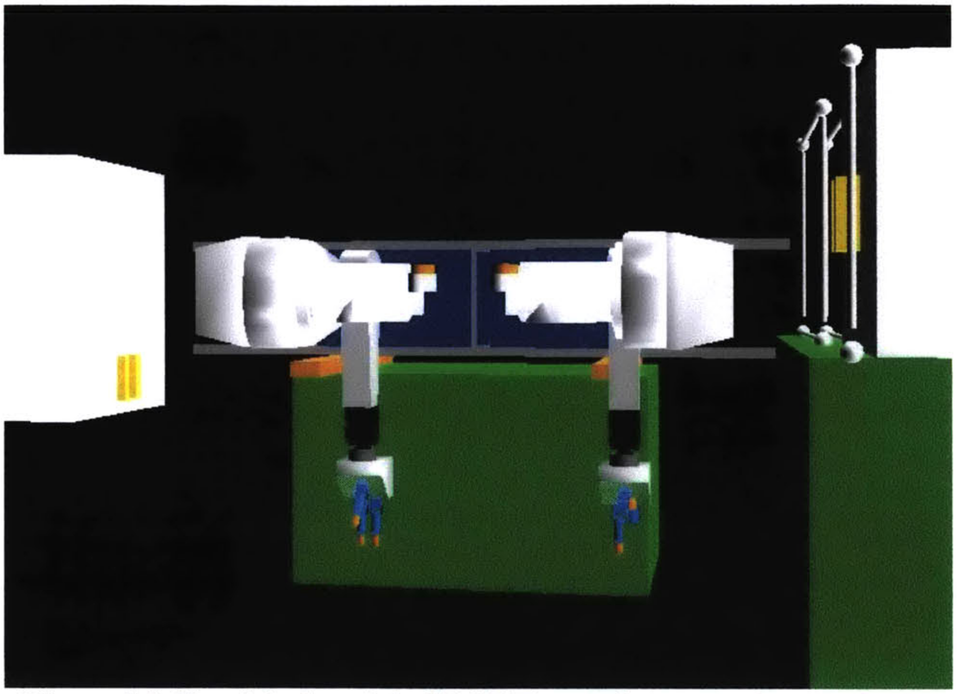


Figure 5.2 Graphical model of DART experiment environment

For comparison, the white cabinet with yellow handles to the right in Figure 5.2 is the same as the cabinet DART is reaching towards in Figure 5.1. The display consisted of an overlay to the HMD live video signal from the DART camera eyes. The overlay was a graphical view of the arms shown in Figure 5.3.

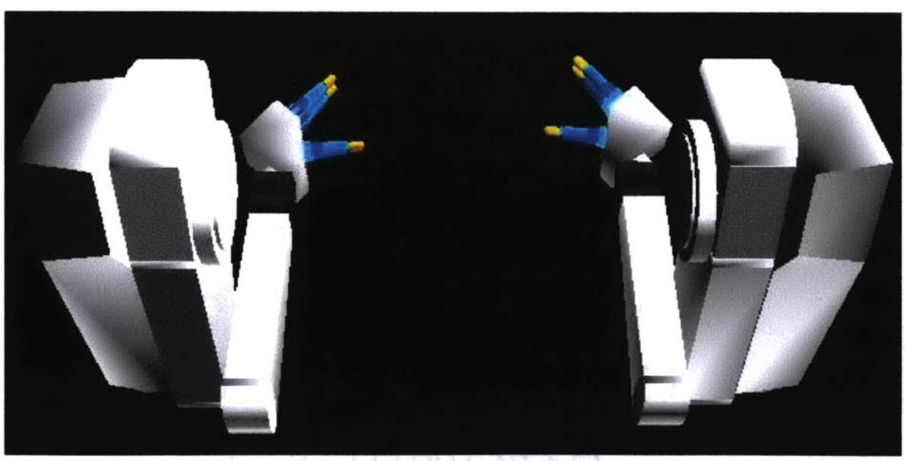


Figure 5.3 Overlay display for DART experiment

A program calculated the minimum distance from the arms to all objects in the environment. Limits were set to indicate three warning levels. If the minimum distance reached the outer limit, the arm segment in question would turn yellow. At the second limit, an orange warning would appear and at the collision imminent limit, the arm segment would turn red (see Figure 5.4).

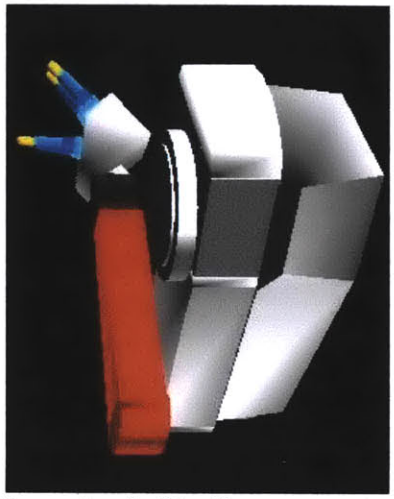


Figure 5.4 View of DART overlay indicating nearest collision warning for the forearm (red)

This display is purely an experimental construction as it is not possible in an operational capacity to exactly model the external environment. However, for pilot study purposes, the construction did serve to indicate the utility of the collision avoidance function. The display solution covered the display requirements in that it provided multiple collision warning level information in an intuitive manner. A graphical depiction of the arms from the inside-out perspective gave an easily interpreted cue as to which segment was in danger of a collision and needed attention.

5.2 DART Results

Performance times for each segment of the tasks were recorded. The average completion times for the ORU changeout and the tool exchange tasks were 861 sec and 750 sec respectively. Figures 5.5 and 5.6 show the completion times in seconds for all subjects and tasks across trial days. Figure 5.7 and 5.8 shows the task time for both tasks combining all subjects for each trial day. The mean is also plotted to show the clear learning trend.

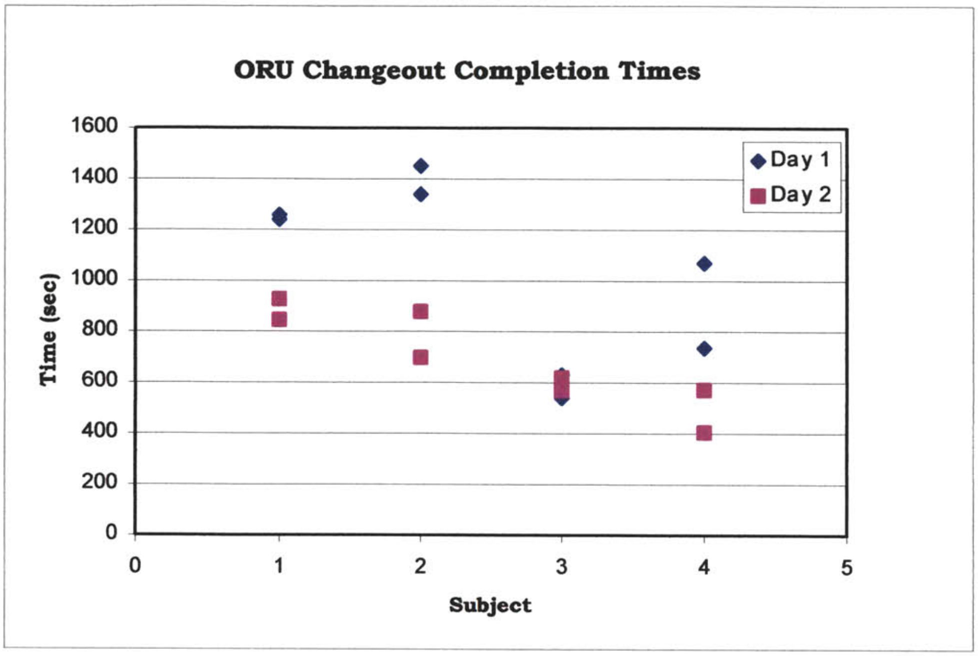


Figure 5.5 ORU Changeout task times for each subject over both trial days

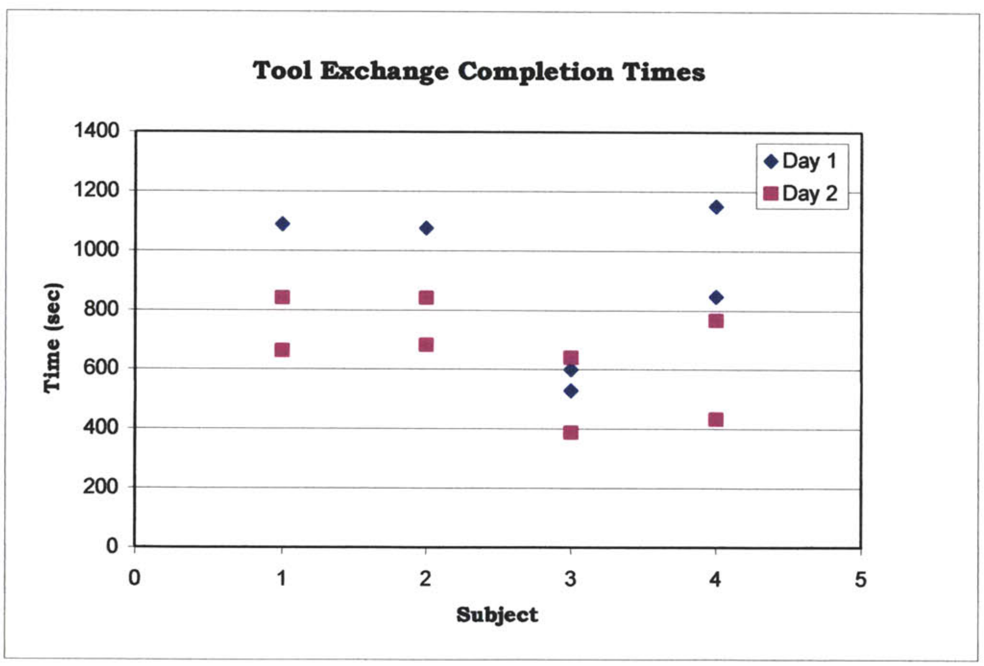


Figure 5.6 Tool exchange task times for each subject over both trial days

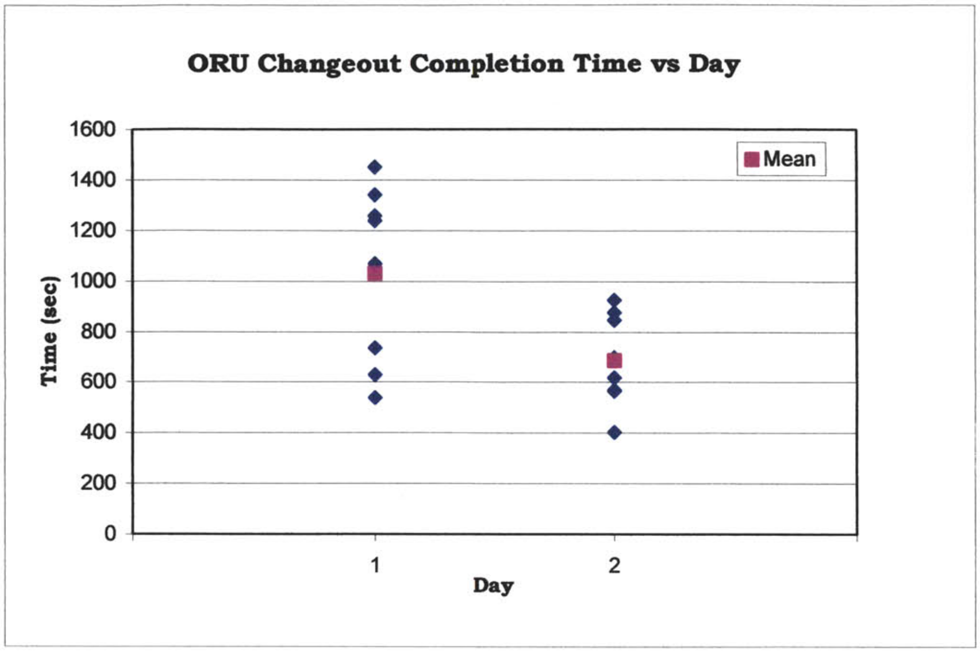


Figure 5.7 ORU task time versus day

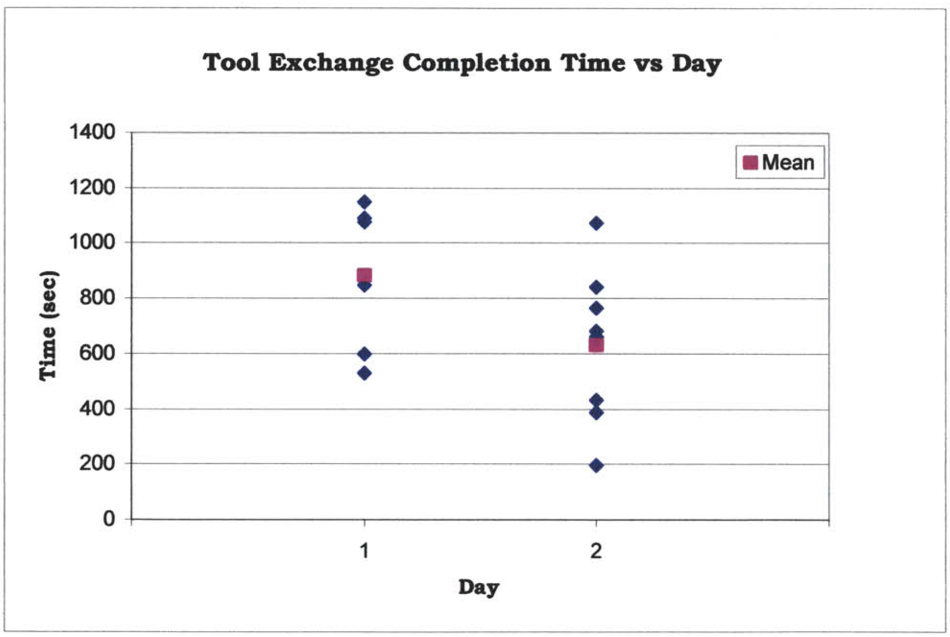


Figure 5.8 Tool exchange

Tables 5.1 and 5.2 list the statistical data for these two tasks from the one-way ANOVA pcalculations including the mean, variance, F-ratio (the ratio of two independent estimates of the variance of a normal distribution) and p-value. The "p" value, or probability value, is a quantification of the statistical significance of a given effect (or the confidence of a statistical measure). For this research, an effect is statistically significant if the symmetric confidence interval is greater than the 95^{th} percentile (or $p<0.05$).

Table 5.1 ANOVA results for the ORU changeout task learning

Task and Day	*N*	*Mean Task Time*	*Variance*	*F*	*P-value*
ORU Day 1	8	**1034**	122638.5714	6.085	**0.027**
ORU Day 2	8	689.75	33146.78571		

Table 5.2 ANOVA results for tool exchange task learning

Task and Day	*N*	*Mean Task Time*	*Variance*	*F*	*P-value*
Tool Day 1	6	**882.833333**	71290.96667	5.643	**0.035**
Tool Day 2	8	576.125	47047.26786		

The above data shows that significant learning occurred across trial days. Note that in Table 5.2, n = 6 for the tool exchange task on day 1. This was due to hardware failures that prevented completion of two of the trials. For the ORU changeout task, the mean task time falls from 1034 seconds to 690 seconds from Day 1 to Day 2. The tool exchange task mean completion times falls from 883 seconds to 576 seconds from Day 1 to Day 2. The significance values for these to tasks are $p_{ORU} = 0.027$ and $P_{tool} = 0.035$. Notice that the variance is large in both cases as is evidenced in Figure 5.5 and 5.6. Subject 3 task times are almost half of other subject's, and less than half in some cases. The variance in task times (for all subjects) on Day 1 was compared with the variance in task times on Day 2. The variance decreased by a factor of 5 for the ORU changeout task, and the tool exchange variance decreased by a factor of approximately 2.5. The variances are plotted in Figure 5.9 with the error bars. This result echoes the significant learning effect that is present across days.

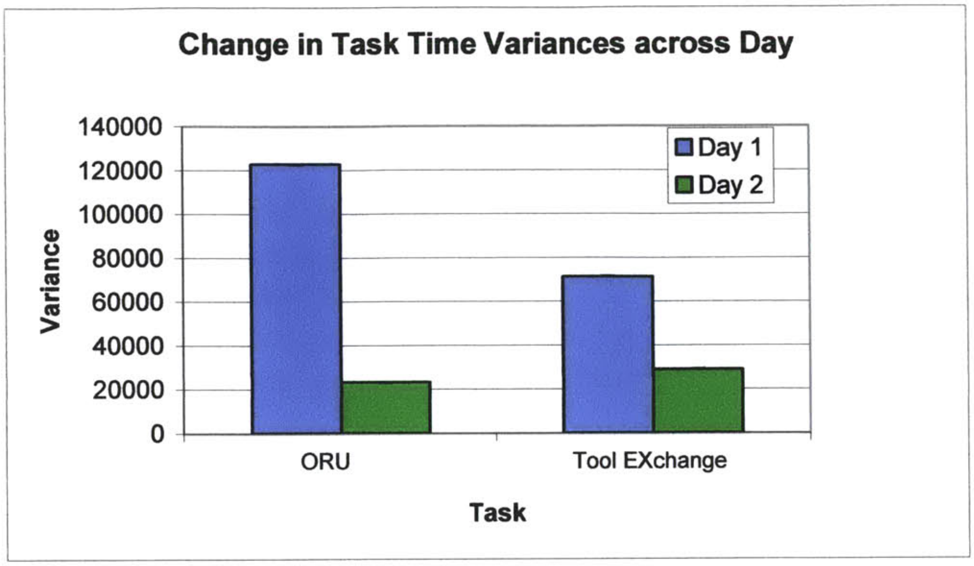


Figure 5.9 Change in task time variances from Day 1 to Day 2 for both tasks

The amount of total task time spent on Situation Awareness was also measured. SA time was defined as the time required for subjects to scan the area between movements or subtasks for a greater sense of the workspace layout and their position within it, and to decide how best to perform the next task given the context of the task as a whole. Since subjects often swept their gaze around the workstation to learn its layout while simultaneously turning, it is difficult to identify all instances when subjects are gaining SA. Thus the SA time reported here represents the time when subjects were doing no tasks other than gaining or maintaining SA.

Table 5.3 compares the SA time and the percentage of SA time across days. Note that the mean percentage of SA time on Day 1 was approximately 10.4% and on Day 2, approximately 11.2% (average of 10.8%).

Table 5.3 Percentage SA time versus day for all subjects and tasks

% SA Time

Day	*n*	*Mean*	*Variance*	*F*	*P-value*
1	14	10.4440738	87.941386	0.05252249	0.82039646
2	16	11.1937672	72.9315306		

The pure SA time is reduced by an average of 32 seconds from Day 1 to Day 2. As the high p value in table 5.3 indicates, there is no statistically significant difference between the percentage SA time on Day 1 and Day 2. This result suggests that although the subject can decrease their task performance time and total SA time with practice, this does not lessen the *percentage* of total task time a subject must spend gaining SA. Figure 5.10 demonstrates that the percentage of time spent on SA did not differ across day in comparison.

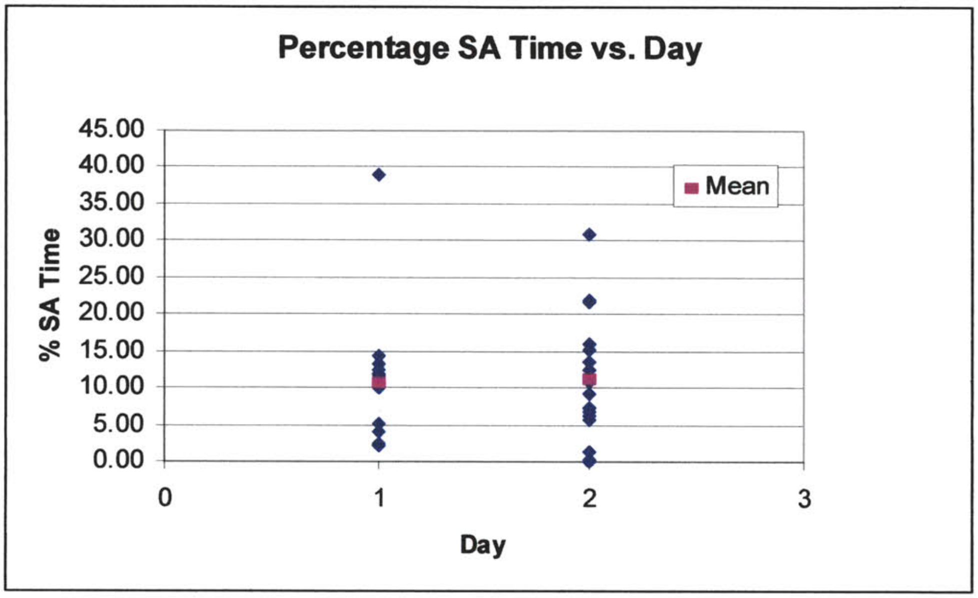


Figure 5.10 Percentage SA time versus day for all subjects and tasks (mean = 10.8%)

Tables 5.4 and 5.5 show ANOVA results for comparisons of SA time and percentage SA time across tasks and days. Results indicate no significant difference with the exception of SA time of the ORU task versus the Tool Exchange task across both days for all subjects. Here, the probability value is very near significance and observing the means in this case indicates that the ORU task required more SA time. Recall that this task also averaged a higher task time (111 sec greater than the tool exchange average). With an increase in both SA time and task time, the percentage SA time would remain constant as is evident from the previous data.

Table 5.4 SA time comparisons between tasks listed for each day

SA Time (sec) - Day 1

Task	*n*	*Mean*	*Variance*	*F*	*P-value*
ORU	8	152.125	21888.125	2.29757424	0.15546664
Tool	6	57.1666667	1650.56667		

SA Time (sec) - Day 2

Task	*n*	*Mean*	*Variance*	*F*	*P-value*
ORU	8	101.125	7680.125	1.51458134	0.23871829
Tool	8	57.75	2257.35714		

SA Time (sec) - Days Combined

Task	*n*	*Mean*	*Variance*	*F*	*P-value*
ORU	16	126.625	14492.1167	4.13762196	**0.05151207**
Tool	14	57.5	1850.42308		

Table 5.5 Percentage SA time comparisons between tasks listed for each day

% SA Time - Day 1

Task	*n*	*Mean*	*Variance*	*F*	*P-value*
ORU	8	13.0866158	126.993631	1.54429532	0.23771481
Tool	6	6.9206843	24.7865465		

% SA Time - Day 2

Task	*n*	*Mean*	*Variance*	*F*	*P-value*
ORU	8	13.1715445	93.8798402	0.8495344	0.37229531
Tool	8	9.21599003	53.4612048		

% SA Time - Days Combined

Task	*n*	*Mean*	*Variance*	*F*	*P-value*
ORU	16	13.1290802	103.07621	2.43076042	0.13020771
Tool	14	8.23228757	39.7095654		

5.3 Discussion

The results from these experiments indicate that although subject's performance increased significantly from Day 1 to Day 2, there exists a baseline percentage of task time devoted to SA that is necessary to complete a telerobotic task. This is very significant because it indicates that a certain percentage of the total task time cannot be used towards task completion directly, rather it must be devoted to gaining and preserving SA. It may be possible to reduce this time, however it is unknown if this time could ever be eliminated with SA displays and aids. Up to thirty percent of the total task time was spent gaining better situation awareness (SA) and the average across *all subjects and days* was 10.8%. This average percentage incorporates time where the subject was solely attempting to increase SA; it does not signify that only 10.8% of the task time was utilized to increase SA. This constant and minimum amount of time was devoted to obtaining and maintaining SA on both days and tasks. This discovery is a result of observing the transitions between basis movements. Designing displays and feedback mechanisms to aid subjects during these task transitions could potentially reduce task times. Had the experiments focused solely on the basis movements rather than on integrated tasks with contextual information, this phenomenon would not have been observed.

Subjective comments regarding the display did not yield numerical results, however they did reveal some important behavior characteristics. Due to the amount of time required to internally calculate the minimum distance values, a lag was introduced into the display. The display would therefore update after the next command sequence had already been updated. Subjects were therefore receiving delayed information regarding their collision status. Because if this delay, subjects viewed the display as a body position indicator rather than a collision avoidance display. It was also reported that three levels of warning was too excessive. They tended to ignore the warning unless it was at red, although because of the delay, it was often too late to correct the robot position. Remarks were made regarding the secondary task collision monitoring. Some subjects felt that to view the display detracted them from their primary performance, while others referred to it often. Finally, subjects reported that because of a lack of reliable collision information, they slowed their movements for safety reasons – allowing them ample time to react in the event that a collision was imminent.

5.4 Design Implications

Now that a minimum amount of necessary SA time has been established, the question becomes, can this amount of SA time be reduced? A reduction in this time would be desirable as it amounts to a reduction in task performance and can lead to an increase in operator errors. The time subjects spend gaining and maintaining SA as a secondary task detracts from the actual operational task time. Second, the greater the amount of time spent away from the primary task performance, the more difficult it is for the subject to return to the task. Once the subject returns to the primary task they must re-determine where they are in the task process and what the next action should be. Uncertainties here could lead to operator errors. The design implications carried into the next iteration will include the desire to reduce SA time in order to increase performance. That specific goal will be accomplished through the development and execution of several integrated Robonaut and Robosim experiments.

6 Robosim Evaluation

You can tell whether a man is clever by his answers.
You can tell whether a man is wise by his questions.
- Naguib Mahfouz

Before Robosim could be utilized for display design iterations, it needed to be experimentally validated. This was accomplished through tests involving basis tasks performed manually, telerobotically and using the simulation.

6.1 Methods

The basis tasks were devised in order to describe baseline teleoperator behavior during fine position and gross position tasks. The basis tasks were designed for simplicity and did not require force sensing or force feedback (although they could be augmented with such). They could be completed and compared across a variety of modalities, including zero-G, and performed using almost any teleoperated robot or manipulator. The basis tasks were comprised of two task panels (see Figure 6.1), one similar to a FITT tapping task, and the other containing a tracing pattern. Although the figure shows the task panels as viewed through the simulation, a physical task board was used for the manual tasks. Each panel combines elements of both fine and gross position movements. The tapping task was primarily a fine position task for the near center targets and approaches a gross position task farther out in either direction. The tracing task required the subject to trace the outer square in one continuous motion, then lift their finger and reposition it to trace the "X" in the center. This combined a gross position and fine re-position motion for this panel. Although both fine and gross position tasks were performed, they lacked contextual information and therefore were not considered integrated tasks. The target positions on the task board were determined after measuring the robot workspace and conferring with the robot engineers that those target distances were within the reachable workspace of the robot and did not induce taxing robot positions.

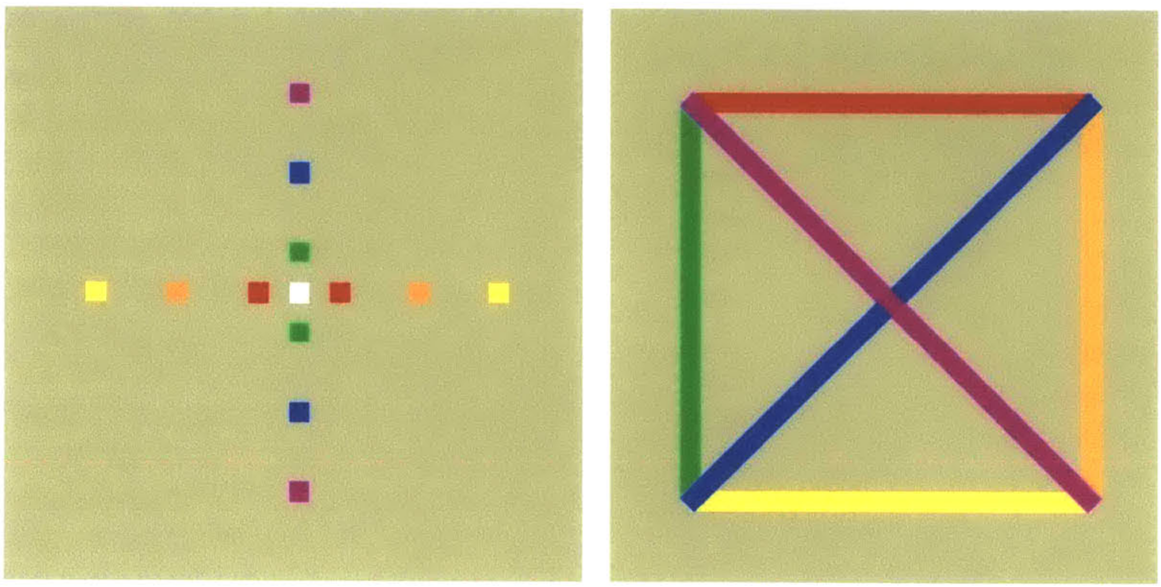


Figure 6.1 Basis task panels

Subjects were instructed to tap between like colors with their index finger. The size of each target was one-half inch square (the approximate width of the Robonaut index fingertip) and they were arranged in both the horizontal and vertical directions. The white target in the center was the starting point for each trial. The red and green targets were one inch from center, orange and blue were three inches from center, and yellow and purple were five inches from center.

The tracing panel involved following a path around the square and through the diagonals with the index finger. The clockwise path traced the red-orange-yellow-green-blue (top right to bottom left)-purple (top left to bottom right) path, and the counterclockwise path began with purple (bottom right to top left) and went in the reverse order. The blue and purple lines were oriented such that subject had to reposition their hand and arm before tracing those lines. Each line was ten inches long and one-half inch wide. The area of the tracing square and the maximum distance from the center to the yellow and purple targets was chosen to comply with the reach envelope of the right arm of the Robonaut. .

The basis tasks were performed in the manual, simulation and robotic (teleoperating Robonaut) modalities. Both the simulation and robot modalities required the use of an HMD, whereas the manual modality did not. To remove the variable of the user's natural vision and keep the wearing of an HMD consistent throughout the three modalities, an HMD outfitted with two cameras on the front of the helmet was worn during the manual trials. This relayed live video of their completion of the manual trials using the same cameras in the Robonaut helmet, giving the same quality of view. Finally, the CyberGlove was worn throughout all of the experiments. Like the HMD, the CyberGlove was not necessary for the manual task but for consistency, the glove was worn during the trials for all three modalities.

6.1.1 Experimental Protocol

Prior to the laboratory basis task experiments, the simulation and basis task panels were flown on board the KC-135 in a small-scale microgravity experiment discussed in detail in Appendix K. Per subjective comments from the KC-135 participants combined with safety concerns, it was determined that the manual tasks should be performed prior to the simulation tasks. In this way, the subjects had the opportunity to practice the task itself before using Robosim. Consequently for the simulation verification testing, rather than applying the various experimental conditions in a random or balanced order, the conditions were applied in a fixed sequence. Manual trials were followed by simulation trials, which were followed by telerobotic trials. Subjects were able to experience the dynamics of the robot through the simulation before attempting to command the robot hardware for the first time. The experimenter also had to opportunity to warn the subjects during the simulation trials of maneuvers to avoid when operating Robonaut, and identified to the subject when poor command generation practices were observed.

The primary design driver for the laboratory experimental protocol was the safety of the robot and the maintenance of its integrity. Robonaut was still under development and the amount of time available for experiments was limited, as was the number of hours the robot could be active and operational in a given day. Likewise, the number of experienced teleoperators was limited to one very experienced (120 hours of Robonaut teleoperation) and two-three relatively experienced operators (20 hours of teleoperation). These restrictions resulted in a protocol that was completed within one day (per subject) with a minimum amount of active robot task time and employed novice teleoperators. The 4 male and 4 female novice operators (ranging in age from 21 to 36) participated in the study in accordance with the NASA Internal Review Board approval for experiments involving human test subjects (see Appendix A). Each subject performed the experiment in one three-hour morning session. The schedule for each trial day was as follows:

(1) Introduction and manual task training (15 min)
(2) Manual basis task trials (30min)
(3) Subjective questionnaire for manual trials (15min)
(4) Introduction and simulation task training (15min)
(5) Simulation basis task trials (30min)
(6) Subjective questionnaire for simulation trials (15min)
(7) Introduction and robot task training (15min)
(8) Robot basis task trials (30min)
(9) Subjective questionnaire for robot trials (15min)

For the manual – basis tasks, the subjects were instructed to tap between like color pairs, or trace the pattern continually until time was called. For the simulated – basis tasks, subjects were instructed to do the same however were told additionally not to penetrate the virtual task board with either their index finger or their hand. Recall that the simulation does not model contact forces. For this reason, operators may pass their virtual hand through virtual objects in the scene with no penalty. As the subject will be operating Robonaut at a later time, it was preferred that the subjects be trained to avoid movements that were not possible with the robot (nor did we want to introduce negative training). For safety reasons during the robot trials, subjects were instructed not to "punch" the board or drag the robot finger along the board. For the simulation and robot basis experiments, there was no force feedback to the operator as to whether contact was made, however subjects could visually observe if any part of the hand went though the virtual task board in the simulation. During the robot trials, subjects could observe the deflection of the task panel if the robot was in contact with it.

All tasks were conducted using the right hand and only right-handed subjects were used. One arm-one hand operations were selected so as to not overwhelm new operators with control responsibility for an additional 19 DOF. For each modality, a session consisted of 32 trials. There were six colored pairs and two tracing directions (clockwise and counterclockwise). Each was performed four times in a balanced order. Following the trials, a subjective questionnaire was administered to the subjects (see Appendix K). The following sections describe each of the individual modalities in more detail.

6.1.2 Manual Tasks

The basis tasks were first performed manually. For this set of experiments, the subject was seated in the laboratory telepresence chair wearing a set of Polhemus sensors on the back of the palm, chest and head (attached to the HMD). The HMD was worn with two cameras mounted on the outside of the helmet. The cameras utilized were identical to those mounted in the Robonaut head to ensure that the field of view and camera quality was the same. Figure 6.2 shows the subject seated with the telepresence hardware in front of the task panel.

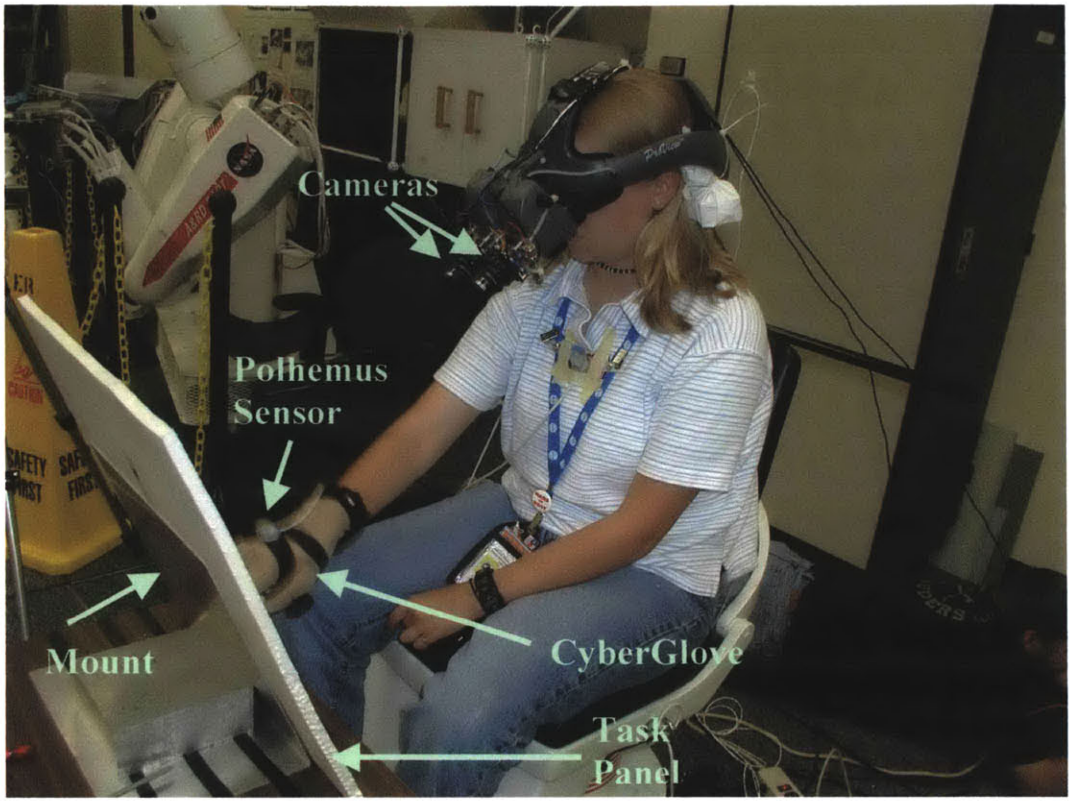


Figure 6.2 Subject completing manual basis task

The task panel was placed on a flexible mount at an angle that matches the angle of the task panel relative to the robot during the robotic trials; during robot trials the panel was placed on an easel in front of the robot and this angle was measured and the flexible mount bent to the same angle. The manual task panel was located at the same position relative to the subject's body as the actual panel was located relative to the robot's body.

Figure 6.3 shows a schematic of the data-path for the manual trials. The right and left HMD mounted camera signals were converted from NTSC (video) to VGA format for the HMD instrumentation unit. The Polhemus sensors were secured to the subject (helmet, hand and chest) and the CyberGlove was worn on the right hand. The data from the sensors were sent to the Robonaut brainstem where they were converted into joint angles. The actual joint angles were published as a data packet. The data packet (common to all modalities) included the joint angles of the 7 DOF arm, the head pitch and yaw angles, and the finger joint angles. The data was sampled at 10Hz and each cycle was marked with a time stamp. In addition to the above data, the input to the HMD (what the subject was looking at) was recorded on VHS and an external Hi-8 camera recorder captured an external view of the subject.

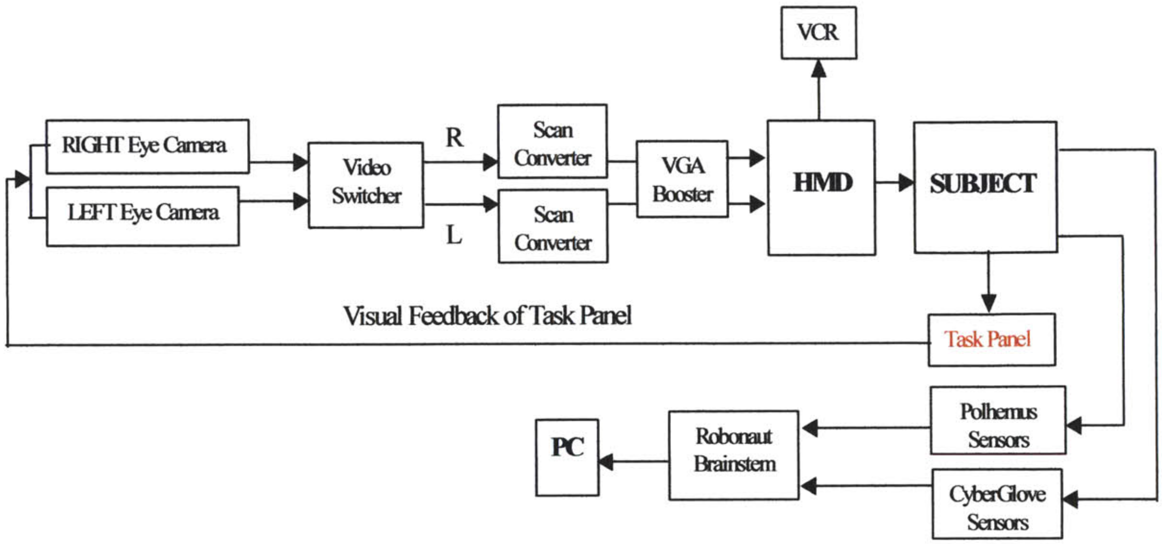


Figure 6.3 Schematic of manual data paths

6.1.3 Simulated Tasks

The simulation modality was the first time that the subjects used the sensors and glove to command a remote object. In this case Robosim, the virtual Robonaut, was commanded. As an introduction to the simulation, the subjects were informed that the dynamics of the simulation were the same as the robot. They were also informed of the joint and velocity limits, were made aware of "dangerous" positions of the robot and simulated robot. The most common teleoperator errors that led to detrimental robot motions were reaching a wrist joint limit, "chicken-winging" the robot arm (see Figure 6.4a) and driving the robot to collide with its own body (see Figure 6.4b). Subjects were told to be aware of the virtual robot position and ensure that they did not drive the simulation arm to collide with the task panel or to collide with other robot segments. Only the arm that was in use during the trials is depicted.

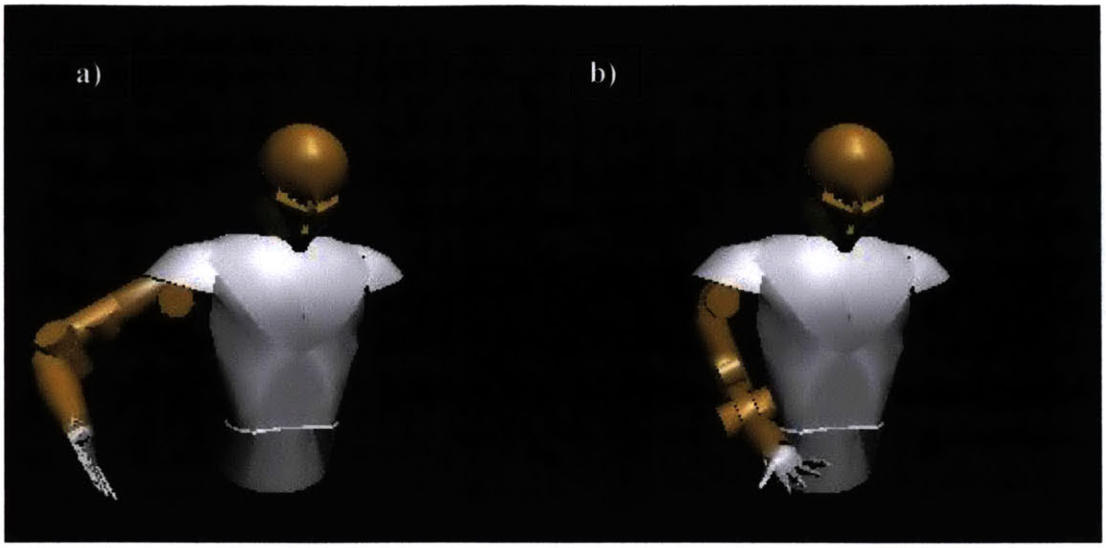


Figure 6.4 Cautionary Robonaut poses (a) chicken wing and (b) self-collision

The subject began the simulation trials by calibrating their hand to the position of the virtual robot hand. The virtual robot hand began pointed to the center target and subjects then pointed to a location in virtual space that was comfortable for them to represent the center of the board. Both the simulation and the robot could be frozen and thawed at any time. As discussed in Chapter 3, to freeze the robot meant that the operator's movements were no longer tracked and they can move at will without commanding the robot. This allowed the subject to re-index (or re-calibrate) their body position with respect to the robot, or to simply rest. This is true of the simulation as well. To calibrate at the beginning, the subject pointed to virtual center where the virtual arm was, thaws the robot, then checked to make sure that their human arm had sufficient travel to reach all of the targets. If not, they could freeze and re-index until a comfortable and efficient mapping has been obtained. It should be noted that the simulation had the hand in a fixed position with the index finger pointing. This was arranged so that the subjects did not have to continually command the hand to remain closed and in a fixed position during the trials. This also reduced the number of degrees of freedom of the task to the 7DOF of the arm.

Subjects were given approximately 5 minutes to practice teleoperating in the virtual environment with both panels, to learn how the simulation (robot) moved in response to commands and the limits of where the arm and hand could travel to without intersecting the task panels. Subjects were reminded that they command the position of the center of the hand, and not the arm, therefore the Robonaut brainstem would determine the appropriate joint angles and trajectories for the arm to reach that position. Figure 6.5 shows a subject during the simulation trials and Figure 6.6 a schematic of the data paths. Polhemus and glove data were sent to the Robonaut brainstem and the returned data packet became the input command for the simulated robot arm. The second computer in the loop schematic was used to generate the second eye view of the task panel so that the subject saw the virtual world in 3-D with depth perception cues. The field of view of the simulation could be manipulated in the Enigma software and was defined to match that of the manual and robotic trials, 60 degrees diagonal. This limit was imposed by the HMD hardware.

Figure 6.5 Subject completing simulated basis task

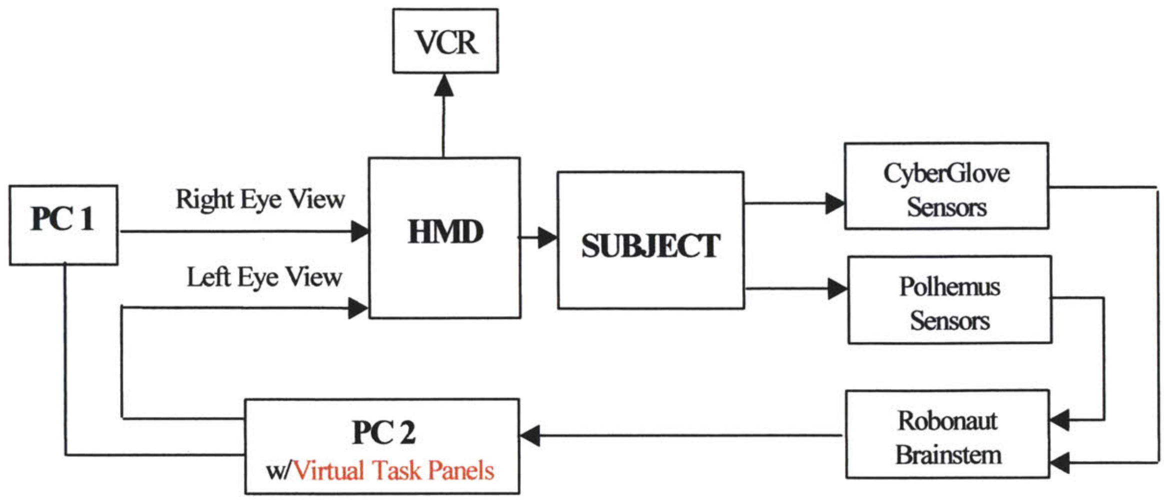


Figure 6.6 Schematic of simulation data paths

6.1.3 Robotic Tasks

The final modality of the basis task testing was robotic. In this set of trials, the subjects moved their arm and head as with the simulation, however the commands generated with the Polhemus and glove were used to command the actual robot. Subjects again sat in telepresence chair wearing the telepresence hardware with the addition of a microphone and headphones that allowed the subject to talk to and hear the experimenter located at the remote robot site. The HMD displayed the stereo view from the Robonaut camera eyes. As an introduction to this modality, subjects were reminded of the detrimental robot poses. As a safety precaution, during all robot trials, an experimenter could verbally warn the subject of a "joint alert" or "collision alert". If the subject heard this warning during the trial they were instructed to freeze immediately, assess the position of the robot and command it to a safe position before continuing. Likewise, if in the event that the robot was in danger of a collision or joint limit that could not be corrected in time, the experimenter could "kill" the robot power.

To begin, subjects were calibrated as before by placing their arm in the same position as the robot arm and thawing. Like the simulation, the hand was frozen and fixed with the finger pointing so that only the arm and head were being commanded. To do this, the CyberGlove was used at the outset to command the hand from a fingers-open pose to the finger pointed pose. Once the finger pointing pose was set, the hand commanding was frozen and removed from subject control. The CyberGlove remained on the hand throughout the trials although it was not commanding after the initial calibration. The subjects were given a few minutes to move around and get used to their new robot body, field of view and vision capability. Next the subjects tested their mapping by pointing to the farthest task panel targets to confirm that there was sufficient human reach to move about the entire workspace. Figure 6.7 shows a picture of the robot being commanded to trace during the basis tasks. The teleoperator and robot engineer responsible for all of the robot systems during the trial have been labeled in the figure. Figure 6.8 shows the schematic for the data paths. Sensor data was read by the brainstem and the output data packet recorded.

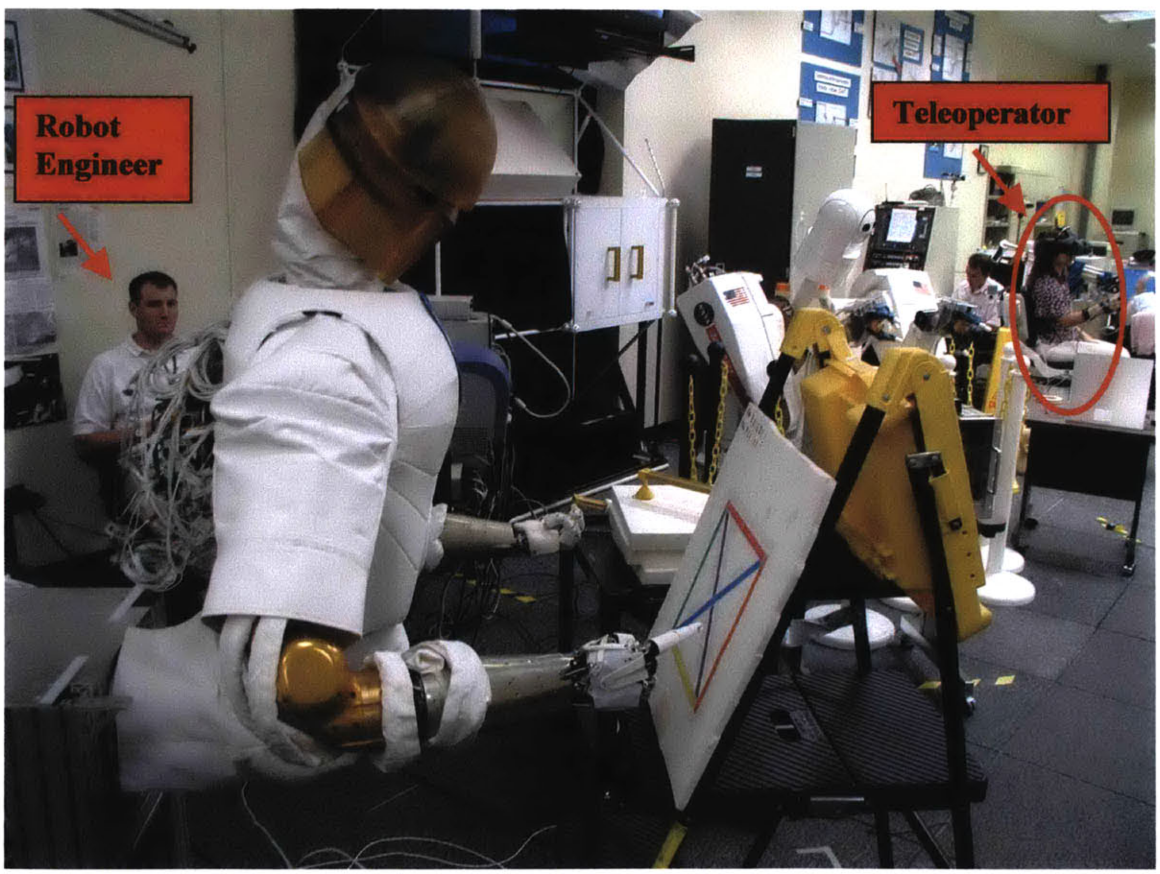


Figure 6.7 Robonaut being commanded by teleoperator during robot basis tasks

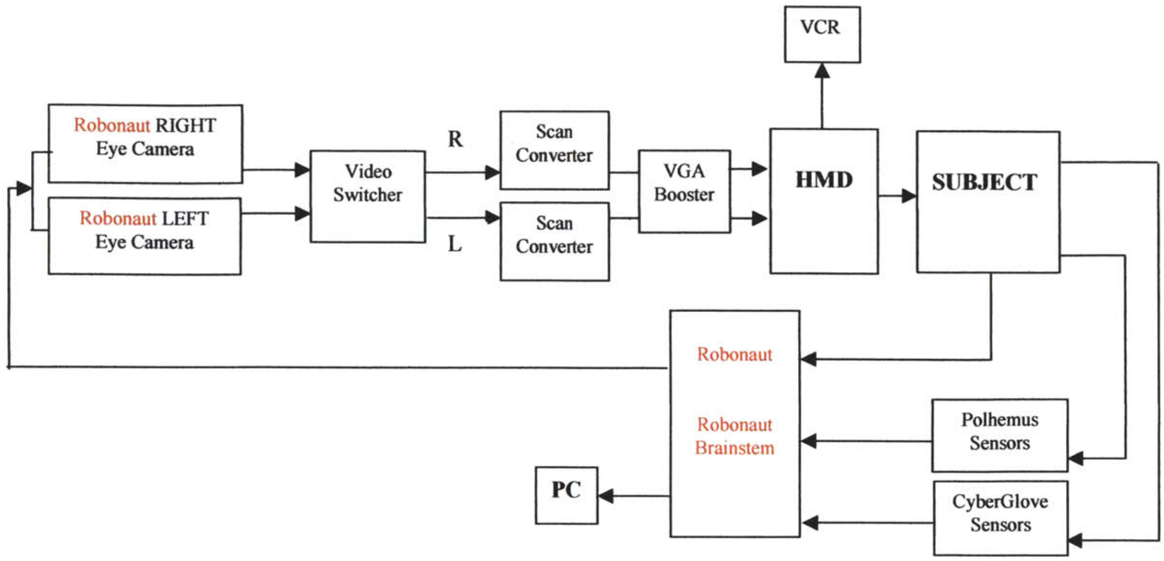


Figure 6.8 Schematic of robot basis task data paths

6.2 Experimental Results

Repeated measures analysis and single-factor ANOVA's revealed the effects of modality, color (distance from center), location (vertical or Horizontal), and gender on the number of taps and number of errors. As expected, the number of taps and traces completed during the manual trials was greater than with the simulation or robot, however across all tasks except one, there is no significant difference between telerobotic and simulated telerobotic task performance (see Figure 6.9). The "p" value, or probability value, is a quantification of the statistical significance of a given effect (or the confidence of a statistical measure). For this research, an effect is statistically significant if the symmetric confidence interval is greater than the 95th percentile (or $p<0.05$). All color tapping and tracing tasks were similar with the exception of the red taps where subjects averaged three more taps with the simulation than telerobotically, enough to make a significant difference over the total number of trials ($P=0.009$) (see Figure 6.10).

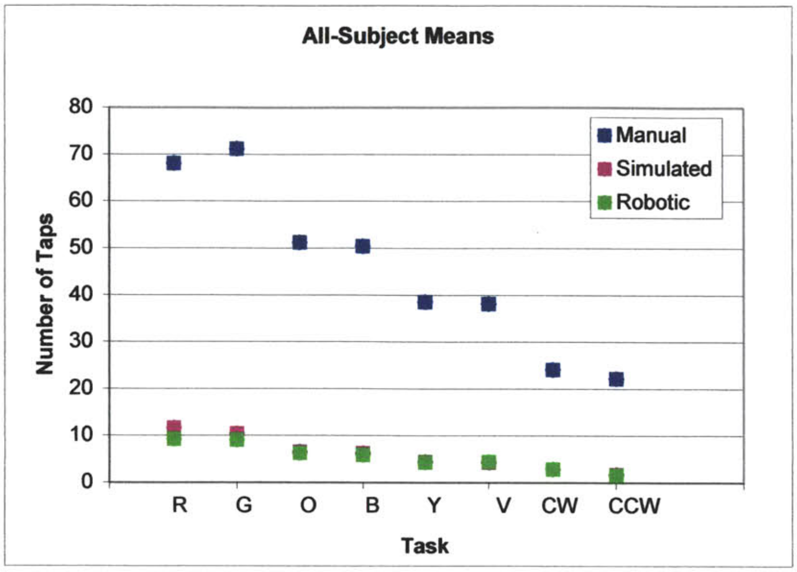


Figure 6.9 Mean numbers of taps and traces for all subjects

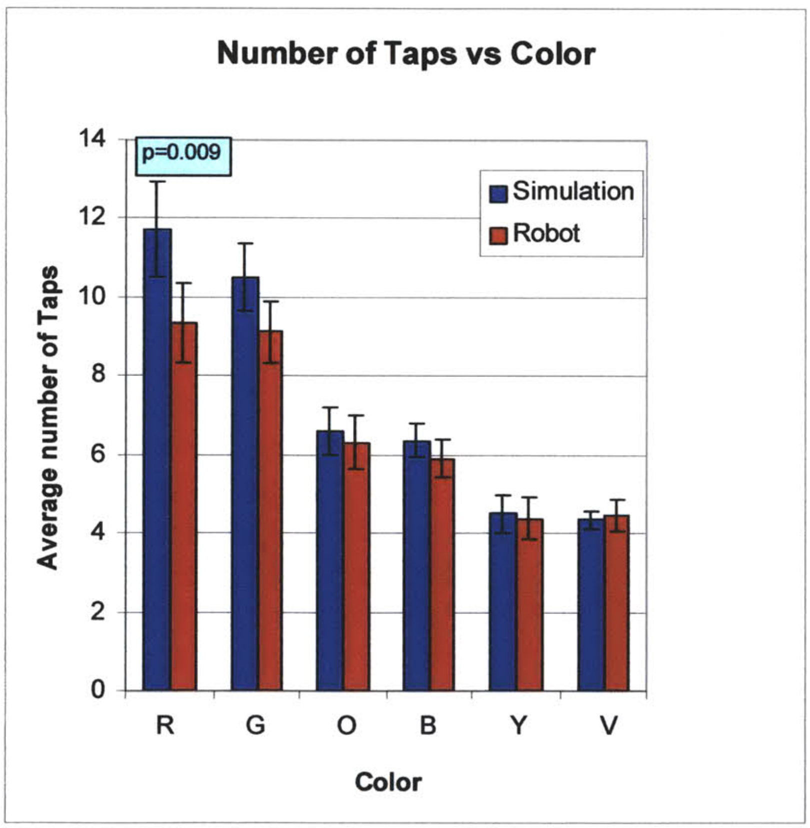


Figure 6.10 Number of taps per color for the simulated and robotic tasks

Table 6.1 lists the mean, variance, F-ratio (the ratio of two independent estimates of the variance of a normal distribution) and p-value for the simulation and robot trials for all subjects. Here we see the only significant difference in the red trials, and also note the low variances for this data set.

Table 6.1 Statistical data for robot and simulation trials for all subjects

RED	*Groups*	*n*	*Average*	*Variance*	*F*	*P-value*
	Simulation	32	12.03125	17.06351	7.08622	**0.009881**
	Robot	32	9.53125	11.16028		
ORANGE	*Groups*	*n*	*Average*	*Variance*	*F*	*P-value*
	Simulation	31	6.903226	8.223656	1.034517	0.313117
	Robot	32	6.28125	3.628024		
YELLOW	*Groups*	*n*	*Average*	*Variance*	*F*	*P-value*
	Simulation	31	4.451613	2.255914	0.025295	0.874168
	Robot	31	4.387097	2.845161		
GREEN	*Groups*	*n*	*Average*	*Variance*	*F*	*P-value*
	Simulation	32	10.59375	9.152218	3.253074	0.076148
	Robot	32	9.3125	6.995968		
BLUE	*Groups*	*n*	*Average*	*Variance*	*F*	*P-value*
	Simulation	32	6.451613	2.922581	0.792304	0.376901
	Robot	32	6.0625	3.092742		
VIOLET	*Groups*	*n*	*Average*	*Variance*	*F*	*P-value*
	Simulation	32	4.40625	0.765121	0.189748	0.66464
	Robot	32	4.53125	1.86996		
CW	*Groups*	*n*	*Average*	*Variance*	*F*	*P-value*
	Simulation	32	3	0.967742	0.054121	0.816821
	Robot	31	3.064516	1.462366		
CCW	*Groups*	*n*	*Average*	*Variance*	*F*	*P-value*
	Simulation	32	1.8125	0.544355	0.018507	0.892229
	Robot	32	1.78125	1.144153		

Figures 6.11 through 6.13 show the average number of taps for each subject and color for the manual, simulated and robotic trials, respectively. Note that the variance between subject averages tend to be greatest toward the center targets and reduce as the target distance increases.

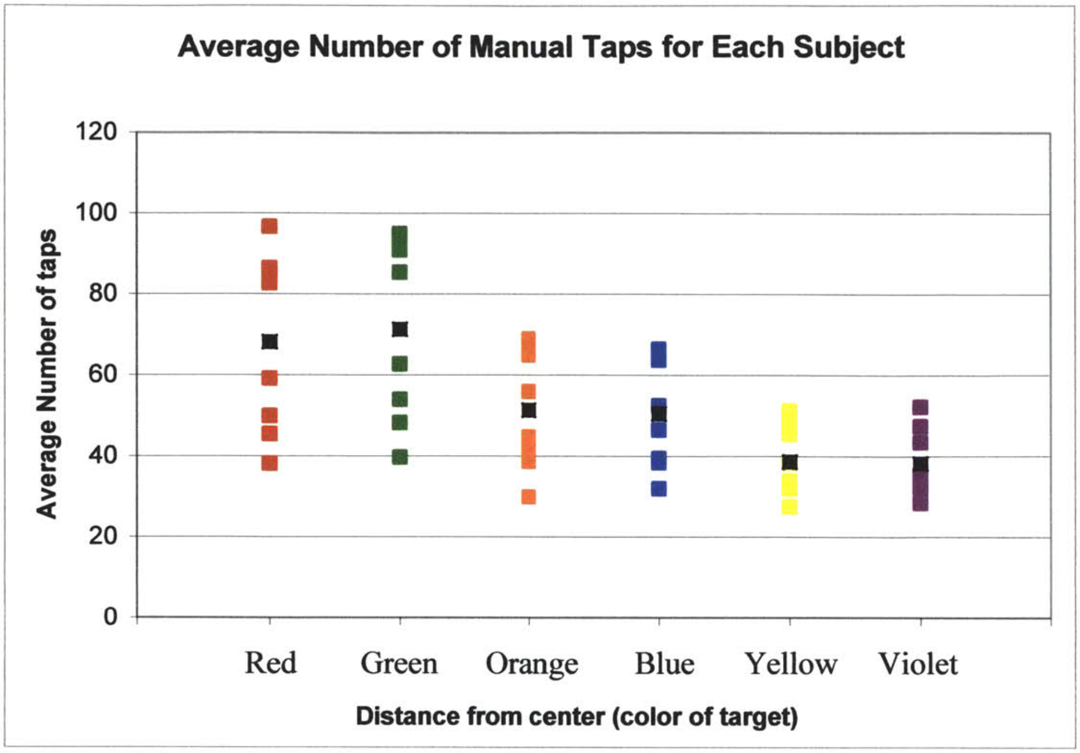


Figure 6.11 Average number of manual taps for each subject and target color

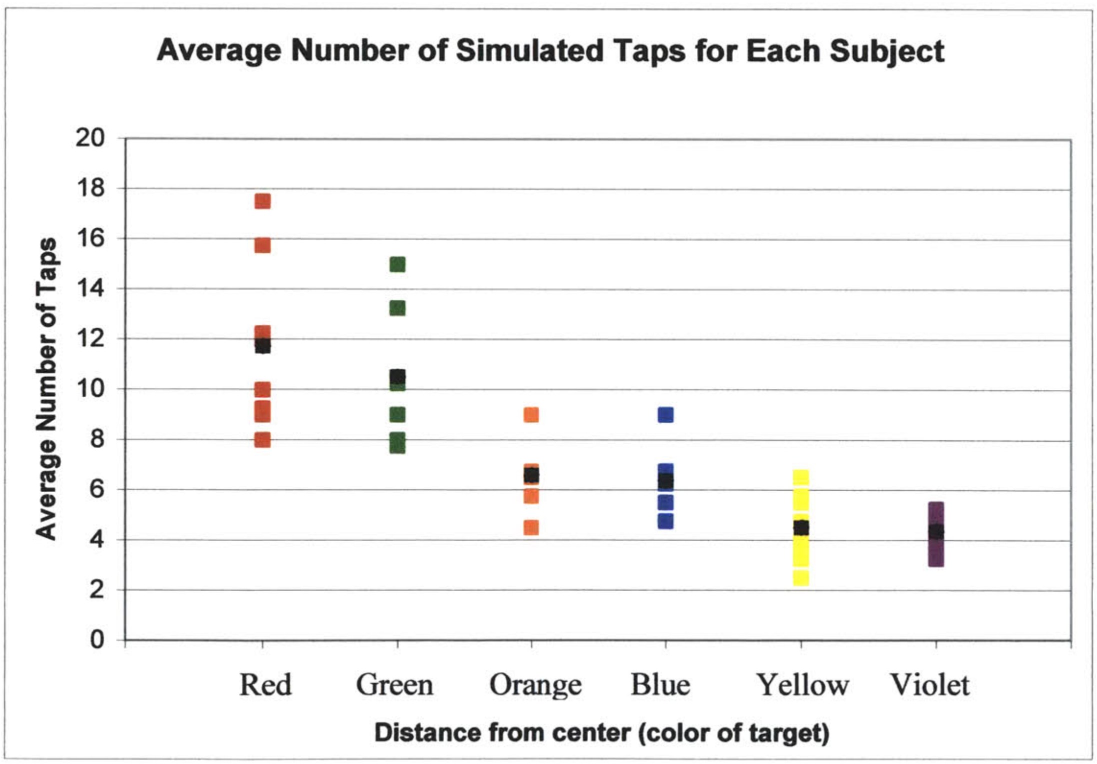


Figure 6.12 Average number of simulated taps for each subject and target color

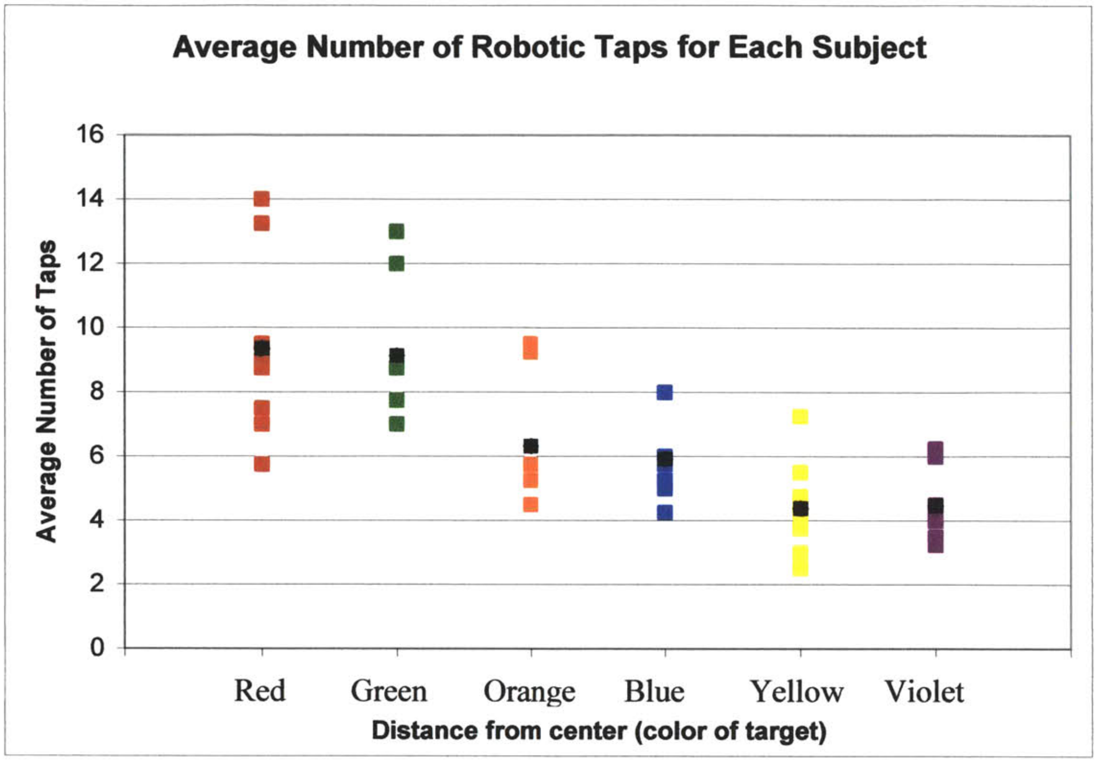


Figure 6.13 Average number of robotic taps for each subject and target color

Table 6.2 lists the comparison statistics for the number of trials with errors between modalities. Errors occurred most frequently during simulation trials (significantly more simulation errors than manual errors). No significant difference was observed between manual and robotic errors, or between robotic and simulation errors.

Table 6.2 Number of trials with errors compared between modalities

Modality	*Count*	*Mean # Errors*	*Variance*	*F*	*P-value*
Manual	8	5.625	15.125	4.948899	**0.043064**
Simulation	8	12	50.57143		

Modality	*Count*	*Mean # Errors*	*Variance*	*F*	*P-value*
Robotic	8	7.375	61.125	1.532054	0.236161
Simulation	8	12	50.57143		

Groups	*Count*	*Mean # Errors*	*Variance*	*F*	*P-value*
Manual	8	5.625	15.125	0.321311	0.579796
Robotic	8	7.375	61.125		

There was no statistical difference between horizontal and vertical directions in the number of taps (See Table 6.3 and 6.4 – top and bottom refer to whether the target is above or below the center white target, and right and left similarly refer to their position relative to the center). However, the number of errors was significantly lower for the vertical targets located below the center target, than for the vertical targets above the center point. There was no difference in horizontal errors between the targets right and left of center. For the vertical colors, the percentage of missed taps across all subjects and modalities was 10.82% above center, and 7.76% below center. For the horizontal colors, the percentage of missed taps was 9.27% left of center and 10.74% right of center. There was no significant difference in the number of traces in the clockwise direction than in the counter-clockwise direction for any modality.

Table 6.3 Errors for vertical targets

	Total taps	Misses	%
TOP	1239	134	10.82
BOTTOM	1095	85	7.76
GREEN	395	45	11.39
Manual	40	1	2.50
Sim	235	27	11.49
Robotic	120	17	14.17
BLUE	883	85	9.63
Manual	611	26	4.26
Sim	156	35	22.44
Robotic	116	24	20.69
VIOLET	1056	89	8.43
Manual	880	46	5.23
Sim	84	19	22.62
Robotic	92	24	22.09

Table 6.4 Errors for horizontal targets

	Total taps	**Misses**	**%**
LEFT	1284	119	9.27
RIGHT	1089	117	10.74
RED	487	60	12.32
Manual	40	1	2.50
Sim	304	42	13.82
Robotic	143	17	11.89
ORANGE	687	72	10.48
Manual	426	13	3.05
Sim	183	44	24.04
Robotic	78	15	19.23
YELLOW	1199	104	8.67
Manual	1040	56	5.38
Sim	95	28	29.47
Robotic	64	20	31.25

6.2.1 Gender Effects

Analysis of gender on the number of taps/traces revealed that for seven out of eight tasks (6 colors, 2 directions), men had significantly larger numbers of taps/traces than women in the manual and robotic trials. For the simulation trials, only the red taps showed a significant difference with men tapping more frequently than women. In all other simulated tasks, there were no gender effects. Although men had more taps and traces than women, they also had more errors. The percentage of errors (missed taps and traces where the subject's finger was not at least approximately 25% within the target or tracing line) within a given trial was significantly higher for men in the manual (p=0.0001) and robotic (p=0.002) modalities than women (see Figure 6.14). There was no effect of gender on the percentage of missed taps in the simulation modality. The percentage of total trials with errors was significantly higher for manual tasks versus simulated tasks (p=0.043). There was no distinction between manual and robotic, or simulated and robotic comparisons. An average of 20% of all of the trials for all subjects combined had errors; manual averaged 17.6%, simulation 37.5%, and robot 23.0%.

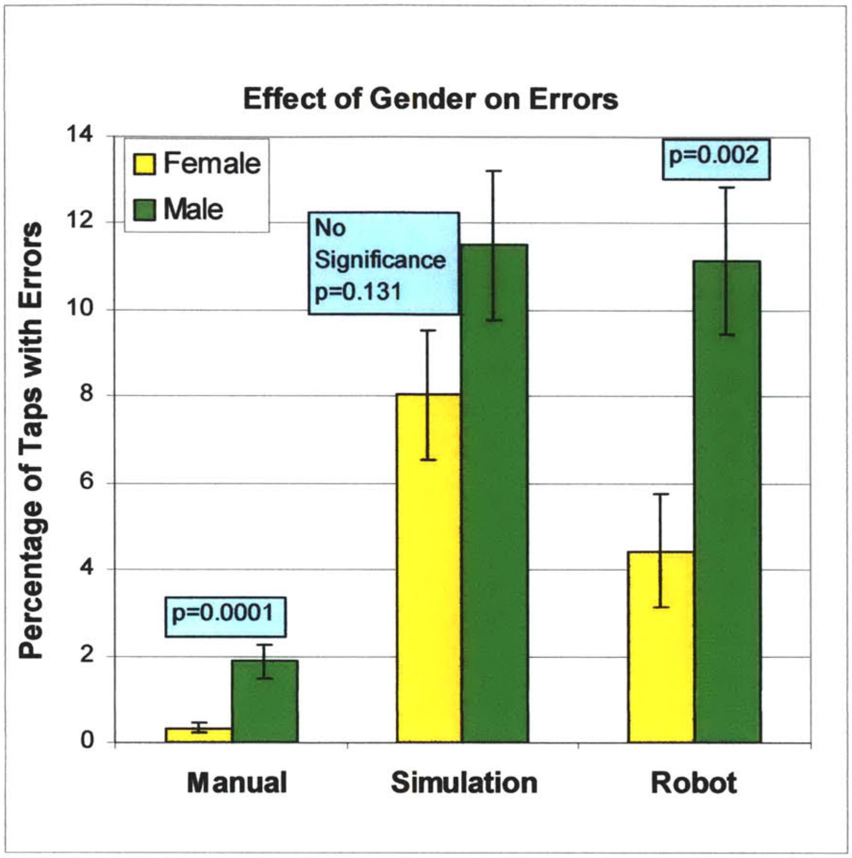


Figure 6.14 Effect of gender on percentage of taps with errors.

Table 6.5 lists the statistical data corresponding to the plot in Figure 6.14 including the means and variances of the percentage of trials with errors for each modality.

Table 6.5 Statistical data comparing gender effects on percentages of errors

% Errors

MAN	*Groups*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	128	0.335892	1.629199	15.21068	**0.000123**
	Male	128	1.868168	18.12846		
SIM	*Groups*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	126	8.04658	282.3786	2.290757	0.1314
	Male	128	11.50031	378.1262		
ROBOT	*Groups*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	127	4.43882	216.1836	9.636694	**0.002124**
	Male	128	11.14358	377.937		

6.2.1 Evaluation Discussion

The simulation and robotic performance was equal for all but the shortest-distance tapping task (red targets) for all subjects. The tendency for subjects to perform the red tapping task faster using the simulation can be traced to the subject's method of tapping. When performing a horizontal task, subjects using Robosim tended to rest their upper arm against their body and swing the forearm right and left, keeping the fingertip in the same plane as if wiping a table surface. Contrastingly, when doing the same task using Robonaut, subjects would hold the arm a few inches from the body, "punch" the target (as if pressing a button), retract the arm, translate it across the center target and "punch" the other side; an in-and-out motion of the fingertip. For the wider targets, the sweeping and punching motions take similar amounts of time, however in the limit as the target separation decreases, the sweeping motion can be accomplished at a greater speed. Since the subjects were instructed to beware of colliding the Robot arm with the Robot's torso, it is not surprising that this strategy developed (as subjects could not rest the robot arm on the robot torso). All subjects tapped between vertical targets using the "punching" method; consequently there was no significant difference for any other color target between the simulation and the robotic modalities.

Validating that the simulation and robotic operations yield the same performance allows the simulation to be used as a design tool and training testbed independent of the robot hardware. Design using an operationally equal simulation offers several benefits. First, each time the robot is utilized for testing it adds wear and tear to the system. If the displays or aids under test are not properly designed, this may increase operator workload, errors and performance times, all of which decrease the robot lifetime. Second, the robot is consistently undergoing upgrades, system tests and reconfigurations; therefore the robot is often simply not available for use in testing. Finally, robot testing requires tremendous overhead in terms of personnel required to run and monitor all systems. A minimum of three people is required to run the robot at this time. Any amount of design work that can be accomplished before testing on the robot will serve as a great benefit both to the designers and robot engineers.

In the training capacity, operators may utilize the simulation to learn the robot dynamics and kinematics, its work envelopes and operating procedures before operating the robot hardware. Training using the simulation is inexpensive in terms of wear and tear, personnel, and availability issues. Additionally, after working in the degraded vision system of the simulation, almost all subjects remarked that the robot was "easier" than the simulation. This is precisely the type of response one would like to elicit from operators, i.e. that the system is easy and intuitive to use.

6.2.2 Teleoperation Discussion

This experimental study has yielded results regarding general teleoperator performance. as well as a validation of a specific telepresence research and training platform. With regards to teleoperator work envelopes, subject performance is not significantly impacted by direction (clockwise or counter-clockwise) or horizontal orientation. Not surprisingly however, the fine positioning capabilities of subjects was greatest in the lower region of the workspace where their human arm could be supported by their body. Not only is the arm in a less fatiguing configuration than when reaching upwards in the workspace, it can be stabilized against the torso for greater precision. One would not expect a difference between right and left targets, as the arm is not resting on the body in either case, as was validated by the results.

The effects of gender on teleoperator performance led to several different conclusions. Men are significantly faster and less precise than women at the fine-position tapping task in both the manual and robotic modalities. The simulation is excluded from this conclusion due to the nature of the visual feedback provided to the subject. The manual and robotic modalities feed live stereo video to the operator and in addition, the live video images are of real three-dimensional objects. Robosim provides a graphical stereo view of computer-generated objects. During manual and robot trials, if the board is touched, the deflection is observed directly (visually). Conversely, as contact forces are not modeled in Robosim, the Robosim task board cannot deflect. The subject must discern contact from careful observation of whether the fingertip has passed through the virtual task board. The non-virtual task board deflection could be sensed through changing light cues in the subject's foveal and peripheral view. Distances and positive contact are therefore better judged with live video, tending to "even out" subject performance in the case of the simulations' limited vision capabilities.

7 Display Design Iteration II

Education is an admirable thing, but it is well to remember from time to time that nothing that is worth knowing can be taught
- Oscar Wilde

This design iteration combines lessons learned from the DART and Robosim evaluation studies that lead to the first Robonaut integrated task studies. First the issues and requirements are reviewed and then the display solution presented. Next the integrated task methods are described and the evaluation performance presented. Finally, the design implications for the next iteration are discussed.

7.1 System Issues

Recall from Chapter 5 that one of the issues that must be addressed with a potential display is its ability to reduce SA time for the operator. A second issue from the DART study was the alternate interpretation of the intended display information due to the presence of an internal time delay. Therefore the amount of background computational processing required to update the displays should be reduced in order to remove any artificial time delays from the system. The system issues could be divided into three categories, safety concerns, task time, and performance. In the DART study, external collisions were the primary focus of the safety issues. Now that the subjects will be performing complex integrated tasks using Robonaut, the safety concerns increase. Results from the Robosim evaluation revealed the two most common safety warnings that were incorporated into the display solution. First, the system issues were as follows:

Safety Concerns

- Robonaut concerns include excessive elbow height, wrist pitch, self-collisions and wear and tear (force)

In addition to the excessive elbow height and self-collisions that has been discussed previously, wrist pitch and excessive force are also high-priority safety concerns for Robonaut operators. The wrist joint is delicate, and excessive pitching of the wrist in either the positive or negative direction can lead to hardware damage. This is particularly the case if force is being applied simultaneously. Wear and tear on the robot is the accumulation of force throughout the trials and also includes discrete excessive force warnings. Within the integrated task protocol there are two aspects of the tasks where there is an opportunity for high forces to be applied from the operator (and no force feedback is available to the operator), and in each case, and experimenter has the ability to end the trial at any time if he/she feels the robot systems are in danger.

- Cartesian control, rate limits and reach limits lead to operator error and instabilities

Since Robonaut is Cartesian commanded, the operator does not have direct control over Robonaut joint angles. Subjects need to be aware that only the hand position matters to the Robonaut kinematics as they perform their task. For example, if an operator keeps their hand fixed while rotating the elbow downwards, this will not lower the elbow of the robot in return unless the hand position is varied. Operators will feel that the robot is not "behaving", or following commands. This also occurs when an operator nears a rate limit or joint limit (singularity). Robonaut has command authority to adjust the joint angles to avoid singularities. It also directly filters the rate at which subject command the arm to move. Often times the subject will command the arm to move too quickly and the arm will appear to lag behind the command. If the operator does not wait to regain tracking before continuing to input command streams, the robot can go unstable and shut down. Likewise, near a singularity, the robot software will drive the arm position away from the limit. This can lead to mode awareness errors if the subject does not recognize that the robot is self-correcting.

Time

- Subject has extremely limited field of view and cannot see body position directly

The limited field of view provided by the HMD prohibits the subject from seeing their body position directly. Time is required to scan for this information if necessary for either self-collision or external collision avoidance. This posture and environment monitoring time will increase task times

Performance

- Need to Maintain SA During Performance but time away from primary task detrimental

Operators need to maintain SA throughout the duration of their tasks, however to do this at present, it requires a scan of their body position and environment. As mentioned above, this by definition increases task time, however it is also disadvantageous to operator performance. It is beneficial to design a display to reduce the baseline amount of SA time for the operators from the previous 10% level. While SA is critical during a task, the amount of EVA/task/test time an operator spends on solely SA and not the task itself detracts from the overall performance objectives and can slow operator progress. Time spent away from concentrating on the primary task can reduce task SA (as opposed to body SA) and when the operator returns to the task, they must re-gain the information and momentum they had when they were diverted from it. While at the very least this will increase the time it takes to re-start task operations, and at most can introduce errors (such as decision, slips or omission errors, for example)

7.2 System Requirements

The system requirements were derived from the system issues. The requirements for this next iteration are as follows:

- Real-time display

In the DART study the time delay prevented the display from being utilized as a collision avoidance display. Alternatively, subjects obtained valuable body position information from the graphical view of the arms. The requirement here is to reduce internal display processing such that no time delay is introduced.

- Intuitive information transfer regarding the operator's SA

The display should be easy to interpret and provide clear and unambiguous SA information to the operator in an intuitive manner

- Increase in performance

The display should lead to an increase in performance

- No increase in operator workload

No increase in operator workload should result from this display. This requirement also echoes the need for easily interpreted information

- Decrease in operator error

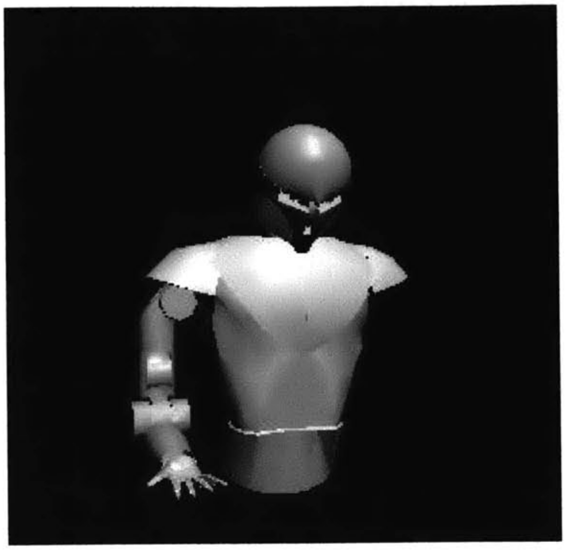
The display should ideally decrease the number of warnings or errors exhibited by the operators during the task. This would result from increasing the operator's SA and mode awareness

- No increase in task time

Overall, the task time should not increase as a result of using this display information. If the display decreases the number of errors and warnings but at the expense of significantly increasing the task time, then the display design is inefficient and more damaging than beneficial

7.3 Display Solution

A display solution was obtained that incorporated the system requirements along with the design implications from the previous studies. The overall structure for the display was an overlay in two forms, a) a full-body view and b) a close-up wrist pitch view (see Figure 7.1. During the basis robot experiments, an engineer gave verbal alert cues to the subject that they were in danger of harming the robot. For these integrated experiments, a visual display was designed to take on that role.



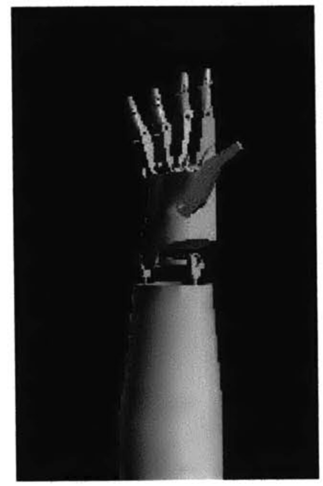


Figure 7.1 Body overlay (left) and wrist overlay (right)

External collision avoidance calculations were removed to mitigate the time delay problems encountered in the previous design and provide real-time position updating. The color of the overlays was chosen for maximum visibility against the live video feed from the Robonaut cameras. The body and wrist views addressed the two most common error warnings from the basis experiments: self-collision and excessive wrist pitch. In addition, excessive elbow height (another common warning) could also be monitored with the body display. The requirement for an intuitive display was satisfied by the provision of an exact graphical model of the robot's anatomy. This model gave important relative distance and orientation cues. If the arm was simply represented by a stick figure, there would be no way to discern the roll values of the joints. Different levels of body opacity were tested in addition to the solid model, and the outside-in versus inside-out representation was compared. When considering an inside-out view of the body, the wire-frame required for visibility of the arm in front of the body needed to be extensive to accurately represent the contours of the body. Given the scale and number of wire frame lines, the grid itself often masked the wrist and elbow. The grid and wire views were difficult to distinguish from the live video feed with this overlay hardware, therefore for maximum visibility, a solid model outside-in view was chosen.

No alphanumerics were included in the overlays to reduce the amount of time required for the subject to gather information from the display. A quick glance at the display should reveal all necessary information to continue on with the task with minimum interruption. 5 display conditions are varied throughout the trials. The display conditions are as follow:

1) Visual Display of Body View Only
2) Visual Display Wrist View Only
3) Both Visual Displays
4) No Displays
5) Body View With Vocal Cuing

1. Visual Display A - Body view only

In this overlay the virtual Robonaut torso and arm is displayed in the subject's upper right corner of the HMD view. The left arm is removed for simplicity as the subject is only utilizing the right arm and hand. As the robot is commanded, the virtual Robonaut overlay is updated in real-time, giving the subject an outside-in view of the robot's limb position relative to the body. As a result, they are able to monitor the position of the arm and check for potential collisions or joint limits.

2. Visual Display B - Wrist view only

This overlay shows a close-up of the wrist position in the upper left quadrant of the HMD view. Since the subjects are instructed to monitor the yaw angle of the wrist in order to avoid excessive wrist pitch and the wrist pitch limit, the wrist angles are shown graphically in real-time.

3. Both body and wrist views

For this condition both of the overlays are displayed simultaneously. The body view remains in the upper right corner of the HMD and the wrist in the upper left, so as to remain consistent throughout the experiments.

4. No overlays

For a control condition, none of the overlays are displayed.

5. Body visual overlay with voice aiding

This display consists of the body display plus auditory cues from the experimenter. In the fifth display case, the experimenter gives specific cues to aid the subject with the peg-in-hole task (fine position). Verbal cues include "up", "left", "too steep", "too shallow" etc. In addition, force warnings are given before an immediate alert condition results.

For safety reasons, it is important to note that for all trials, regardless of the display condition, an experimenter would verbally alert the subject if the robot was in danger of being damaged at any time. This person also had the ability to kill the robot power and end any trial if they felt the robots' health and safety was compromised.

7.4 Integrated Task Testing

Two representative EVA tasks were performed telerobotically that were comprised of different numbers and orders of basis movement including tool transfer tasks, in both the horizontal and vertical planes. Similar to the basis tasks, the integrated tasks were performed with both the HMD and robot arms, or fully immersed. However, the integrated telerobotic tasks were designed to test teleoperator performance during contextual tasks composed of a series of basis movements over five display conditions The first task involved picking up an EVA handrail and placing it on a suspended hook. The second task required subjects to remove a power drill (similar to the EVA Power Gripping Tool) from a soft stow location, translate it and re-stow it in a second location (Figure 4.3). Since the robot was employed for these tests, grasping and hand manipulation were introduced to the subject here. Grasping and tool manipulation is of course, an integral part of both EVA and robotic operations. Along with gross position and fine position movements, grasping completes the set of basis movements under study here. The integrated tasks were not performed on the simulation as the simulation did not model contact forces and therefore could not model grasping tasks.

7.4.1 Integrated Tasks

This section outlines the two integrated tasks subjects perform during the integrated trials. The realm of possible tasks was narrowed significantly given the application of several safety limitations. The work envelope was strictly defined to avoid nearing reach limits. To reduce wear and tear on the robot system, the length of the tasks, forces applied and the number of repetitions were minimized. Subjects were novice operators, therefore grasping had not yet been practiced in any of the other experiment modalities. It was desired to keep the grasping simple, and the tools grasped large and forgiving in the number of possible grips. Other characteristics of tasks were expressly chosen to cover a variety of gross position and fine position movements, using both translational and rotational motions and to include tools most often utilized by EVA astronauts. The two tasks chosen were a handrail grasp and transfer task, and a power drill grasp and transfer task. Handrails and power drills/screwdrivers (called Power Gripping Tool in the EVA arena) are very commonly handled interfaces in EVA operations. Figure 7.2 contains photographs from each of the integrated tasks.

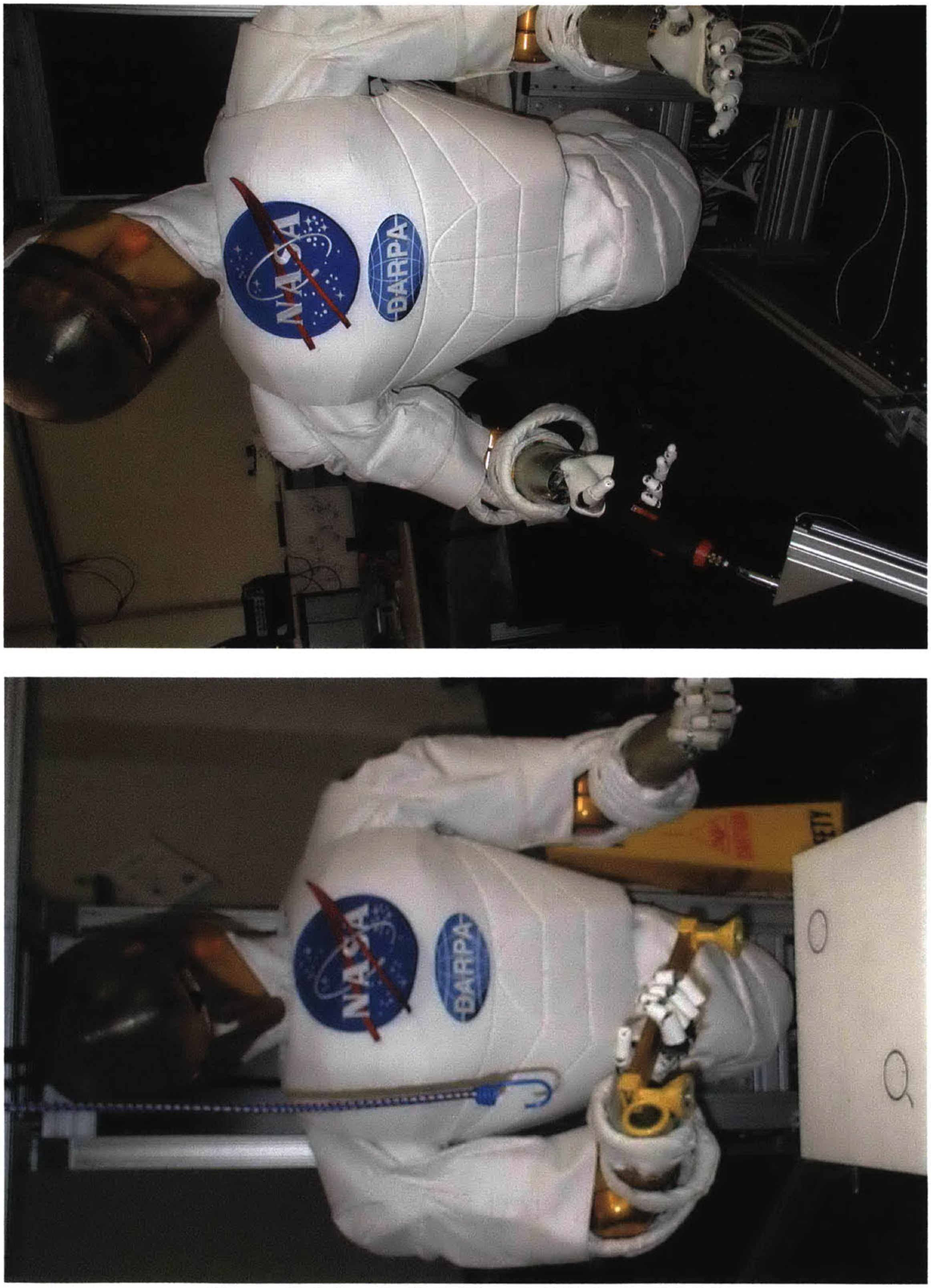


Figure 7.2 Handrail (left) and drill tasks (right)

Handrail Task

The handrail task set-up is shown in Figure 7.3. In front of the robot was a movable cart with an EVA handrail placed on a foam surface. The handrail contained a loop at one end. Hanging from the task stand above was a flexible cord with a hook. Instructions were as follows:

1) Start at the home position
2) Bring the hand to the handrail
3) Grasp the handrail (using an underhanded grasp)
4) Bring the handrail up vertically until the loop is aligned with the hook
5) Align and place the loop over the hook
6) Release the handrail and back arm away

Figure 7.3 Photograph of integrated handrail task set-up

Figure 7.3 shows a mid-task snapshot, just after the handrail has been grasped and lifted. The black circles on the foam indicate where the handrail is placed at the beginning of each task. The small black line on the foam near the outermost circle (noted by the red arrow) indicates the location of the loop at the outset. Several important features of the task should be noted. First, the handrail and foam was placed on a movable cart.

Allowing the cart to move reduced the likelihood that the novice operator would apply excessive force on the foam, and in turn, the wrist, when attempting the underhand handrail grasp. Giving the cart compliance would, in the case of high forces, roll the cart and relieve some of the stress on the wrist. Second, an underhand grasp was chosen for simplicity for the novice operators. The home position placed the arm with elbow bent, in towards the body with palm up (see the left arm in the home position in Figure 7.3). To grasp the handrail overhand involved a forearm roll. Due to the Robonaut joint and torque limits, this motion was not as straightforward as a simple human forearm roll. In an effort to minimize wrist pitch, the robot would often raise the elbow up high. In addition, once the handrail was grasped the subject then needed to rotate the rail and with the arm low near the cart; there was a danger that this motion could drive the elbow down nearing a potential collision with the cart.

The challenge with the underhand grasp was to avoid stressing the wrist due to excessive pitch when coming at the rail from underneath. However this joint was in view and easily monitored, therefore was less of a safety risk than an overhand grasp and a potential obstructed collision. The handrail was placed in front of the robot and angled (as opposed to placing it to the right side and oriented orthogonally to the arm) to force the subjects to utilize the left side of the workspace while minimizing stress on the wrist yaw joint. Finally, the cord hung from the test stand is compliant. Again, the subject did not receive force feedback during the tasks. It was possible that when placing the loop on the hook that the subject would pull down with a good amount of force while trying to release their grasp. If the cord stretched in proportion, this would give the subjects and indication of the amount of force they were applying and they would be able to adjust their motions before releasing the rail.

Timing the trial began when the arm first moves down toward the rail and ended when the robot hand was clear of the handrail after it has been released. If at any point the experimenter deemed that the wrist was under high force or stress during the grasping stage, they could direct the subject as to how to correct for it and/or stop the trial if necessary. If the handrail is dropped or the subject had an insufficient grasp on the rail, the experimenter would correct the grasp before the trial was resumed. The time required to do this was not counted in the total task time, but the error was noted, as was the time required to correct it. If the subject determined that they were not optimally mapped and are nearing reach limits when attempting to grab the rail, they were permitted to freeze and re-index. During the trials, the subject would often re-index before the start of a trial, and if necessary during the trial. Again, this time is not counted against them, but the actions were noted.

Drill Task

The drill task required movement in the horizontal plane as opposed to the primarily vertical plane motions for the handrail task. Figure 7.4 shows the drill task set-up.

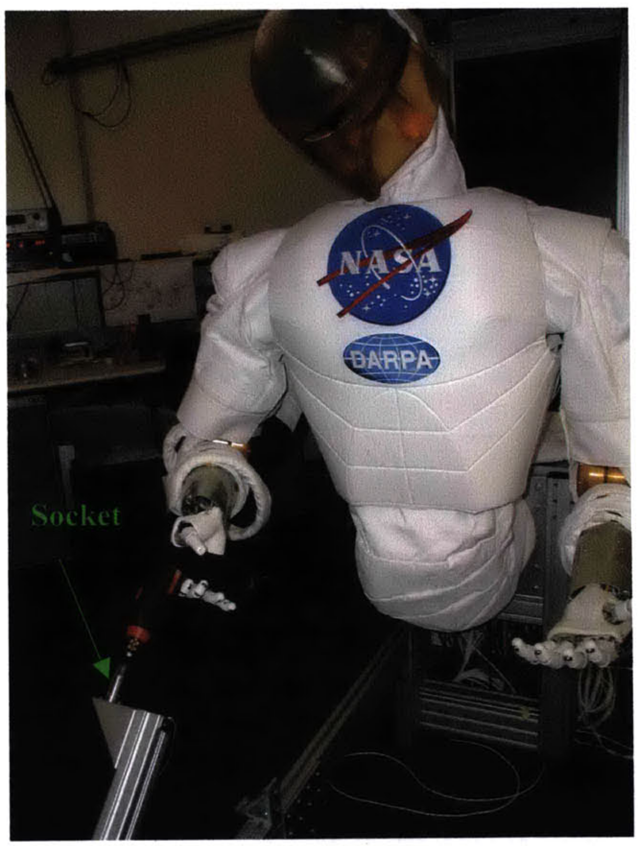


Figure 7.4 Photograph of the integrated drill task set-up

This figure shows a moment near the end of the trial. The task consisted of a stanchion that had a socket attached to it. The stanchion could swivel about its base and during the trial. The instructions for the drill task were as follows:

1) Begin at the home position
2) Bring arm to drill (stowed in socket on stanchion)
3) Grasp drill and remove it from the socket
4) Translate the drill to the stanchion at its new position (stanchion moved by experimenter)
5) Insert drill into socket
6) Release drill and back arm away

Once the subject completed step three and removed the drill from the socket, the experimenter repositioned it so that the subject needed to translate the robot arm to their right to redeposit the drill into the socket. The stanchion was relocated near the edge of the reach envelope of the robot and the task as a whole focused on the right side of the work envelope. With the lack of force feedback, actual screwing and un-screwing of bolts was voted against. In light of their inexperience with the dynamics of a closed kinematic chain of robot segments, application of force and torque could be precarious. The drill task did however include a stowing of the drill, a peg-in-hole maneuver that involved closing that kinematic chain and presented an opportunity for applying force and torque to the wrist. The drill is outfitted with a ¼" extension and a ½" socket. This then inserts into the stanchion's 11/16" socket.

Trial time was recorded from first movement towards the drill, until the hand cleared the drill after it had been released. In the event that the drill as dropped at any time, or if the subject had an insufficient grasp on the drill, the experimenter would correct the grasp and the task continued. As with the handrail, the time required to do this was not counted in the total task time. Similarly, re-indexing was permitted during the trial if necessary. If the experimenter determined that excessive force was being applied to the robot during the drill insertion portion of the task, they would warn the subject and/or stop the task if the safety of the hardware was in jeopardy. Finally, the experimenter verbally told each subject that they were completely in the hole and could safely release the drill.

The hardware and software responsible for presenting the graphic overlays to the user included 2 PC's, 2 overlay boxes and the simulation. Two PC's (one to generate each eye view) ran the simulation; one in command mode and one in listen mode as described in Chapter 3. The structure file consisted of the entire robot in both display cases, but only the wrist was drawn for one display, and the robot minus the left arm for the other display. Each PC was outfitted with it's own Deltascan Pro [Vine Micros Ltd, Kent UK] overlay box which combined the live video signal from the Robonaut cameras with the graphic overlay generated on the computer. This combined signal was then output to scan converters and subsequently to the HMD.

7.4.2 Integrated Task Protocol

Each of the subjects completed 20 integrated robot trials in one afternoon session lasting approximately 60 minutes. With five display options and two tasks, each display-task combination is performed twice (for a total of twenty), and presented in a balanced order. Before each trial began, one experimenter readied the hardware, another changed the overlays and a third confirmed all parties were ready to begin, then started and stopped the data recording. The experimenter in charge of the robot safety and hardware would verbally signal to everyone that the hand had cleared the drill or hardware with the word "done". At this point, the subject returned to the home position and was frozen and allowed to rest until the next trial was prepared. Lastly, joint angle data was recorded, as well as video of both the view through the HMD that the subject was seeing, and an external view of the robot performing the task.

7.5 Results

7.5.1 Effect of Display on Number of Errors

An error for the integrated trials is defined as any one of the following:

1) Reach Limit
2) Tool Drop
3) Kill Switch Activated (due to collision)
4) Excessive Force
5) Excessive Wrist Pitch

The effect of the display on the number of errors showed that the average number of errors per trial was lowest with the third display case where both the body overlay and the wrist overlay were in view, although not significantly. For the handrail task, both the body only and both display conditions elicited the fewest errors. For the drill task, the control condition and both display condition yielded the fewest number of errors (see Figures 7.5 and 7.6). The types of errors were infrequent therefore no significance tests for errors across the displays could be performed. However, the trend indicates that when the body display was not present (as in display 1) or it was present with the auditory commands, there were grater instances of errors.

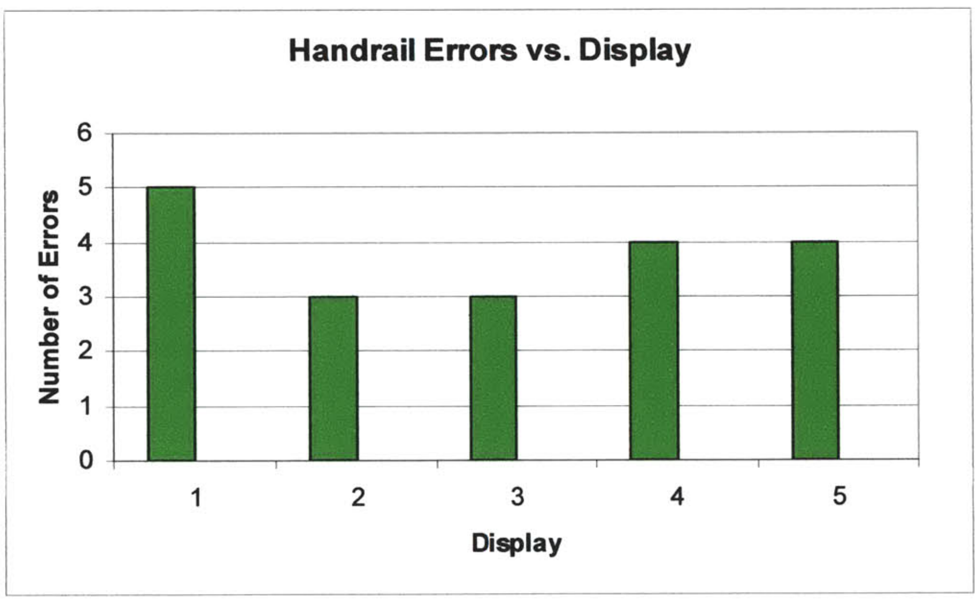


Figure 7.5 Number of errors per display condition for all subjects

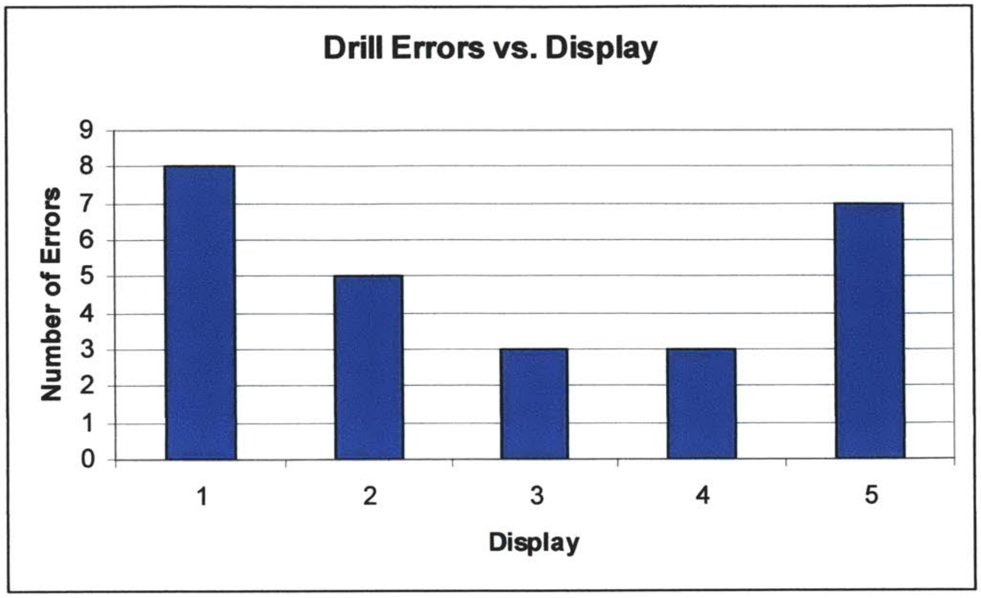


Figure 7.6 Total number of drill task errors per display

Table 7.1 lists the statistical data comparisons for errors between the handrail and drill tasks. 45 trials had errors of which 19 were made during handrail trials, and 26 during drill task trials.

Table 7.1 Number of errors compared for each task

Tasks	*n*	*Sum*	*Variance*	*F*	*P-value*
# A Errors	45	19	0.249495	2.182186	0.143186
# B Errors	45	26	0.249495		

7.5.2 Effect of Display on Task Time

The effect of the display on the task completion time was calculated. Figures 7.7 and 7.8 show the average task completion time for the handrail and drill tasks (respectively) versus display condition. Display one is wrist view only, display two is body display only, display three is both wrist and body, display four is no display, and display five is the integrated voice and body display. Figures 7.9 and 7.10 show the task time variances as a function of display for each task. In both instances the variance is the lowest with the body only display. Statistically, there are no significant effects of the display on the task times for either task. The average completion time for the handrail task across all subjects was 43 seconds, and for the drill task was 59 seconds.

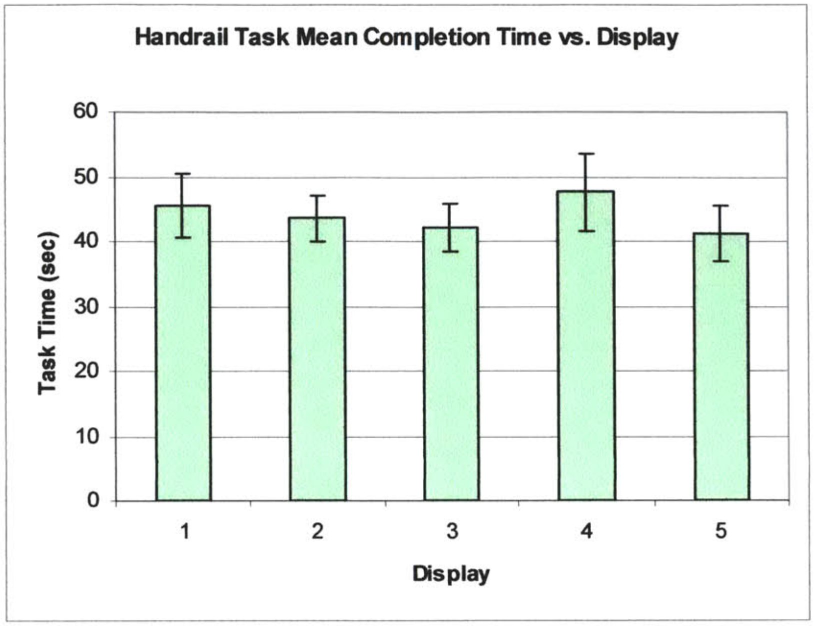


Figure 7.7 All-subject task times versus display for the handrail task

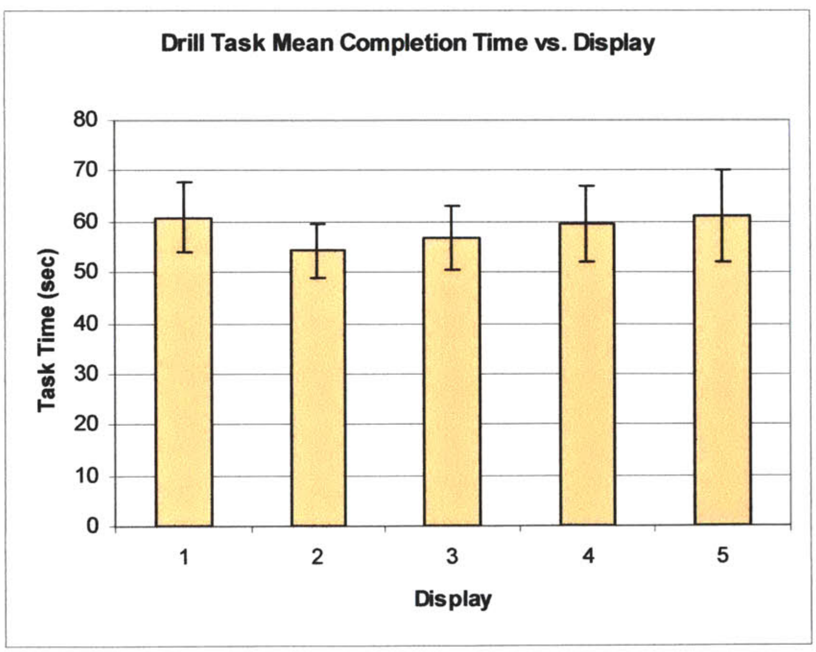


Figure 7.8 All-subject task times versus display for the drill task

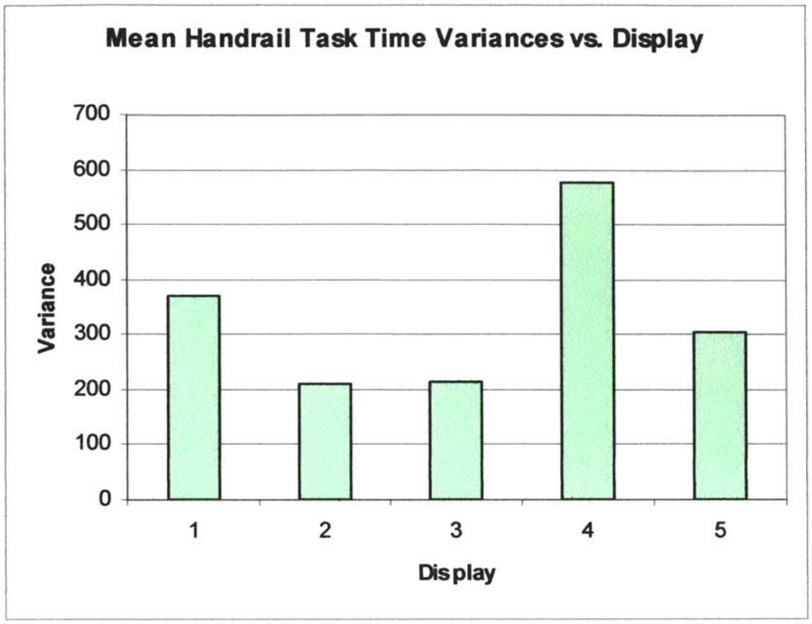


Figure 7.9 Average task time variances versus display for the handrail task

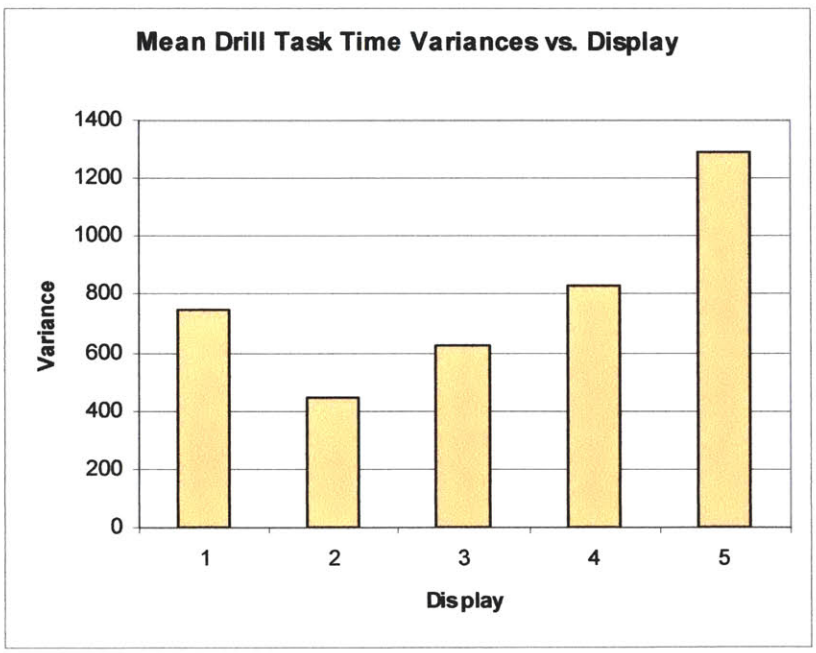


Figure 7.10 Average task time variances versus display for the drill task

Figure 7.11 shows the task time variances for all tasks and subjects versus display. Again, the body only display condition produces the lowest task time variances.

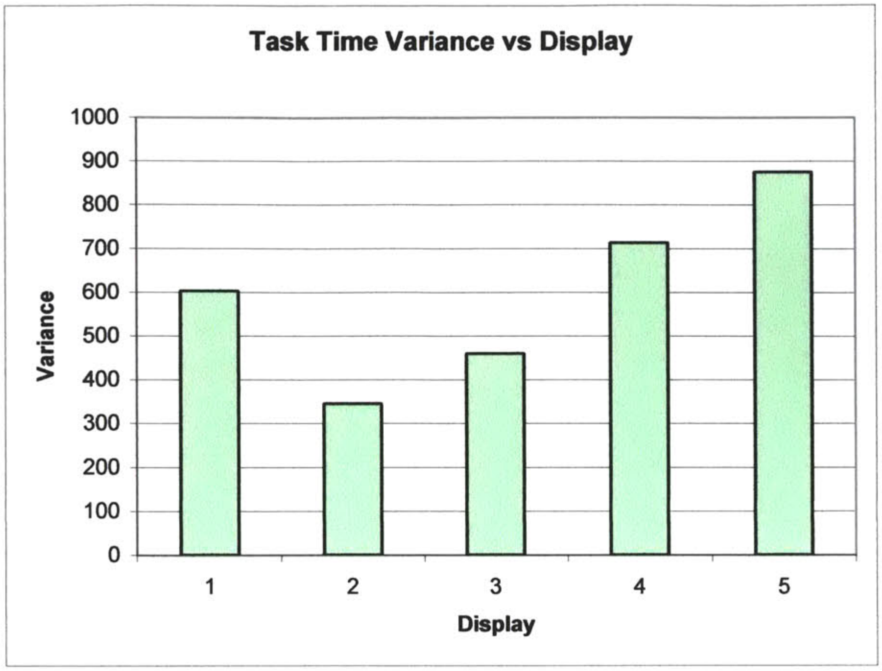


Figure 7.11 Task completion time variances for all subjects and tasks versus display

7.5.3 Effect of Display on Situation Awareness Time

Situation Awareness time was calculated from the recorder and video data, similar to the DART experiment methods. The following results show the effect of display on the SA time for the individual tasks as well as the combined tasks. Figure 7.12 shows the average SA time versus the display conditions for both tasks. Figure 7.13 shows the average percentage of total task time spent on SA (% SA Time) versus display for both tasks. Table 7.2 lists the SA statistical results from a comparison of SA time between the two tasks. The drill task showed a larger SA time (although not statistically greater).

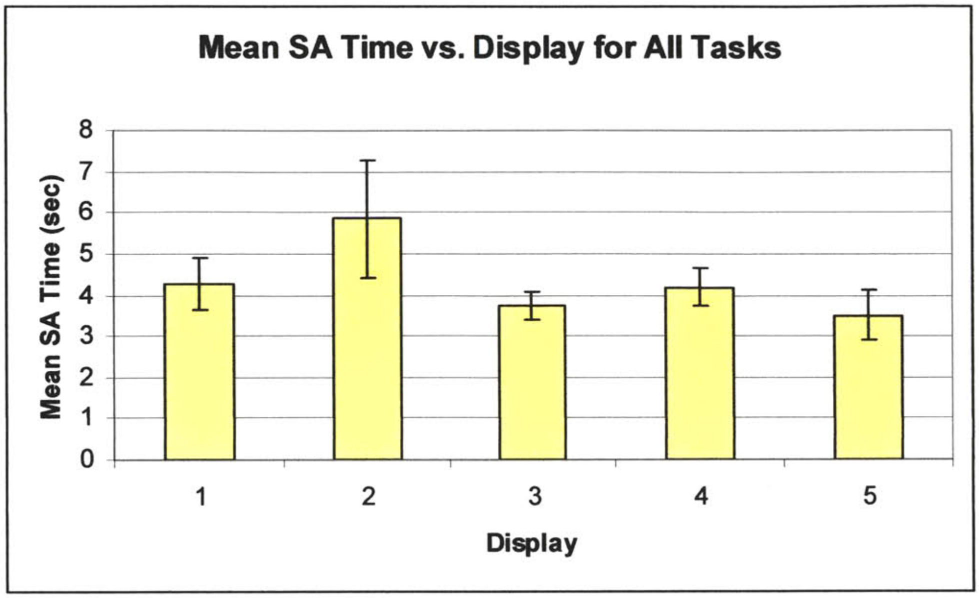


Figure 7.12 Mean SA time versus display for both tasks

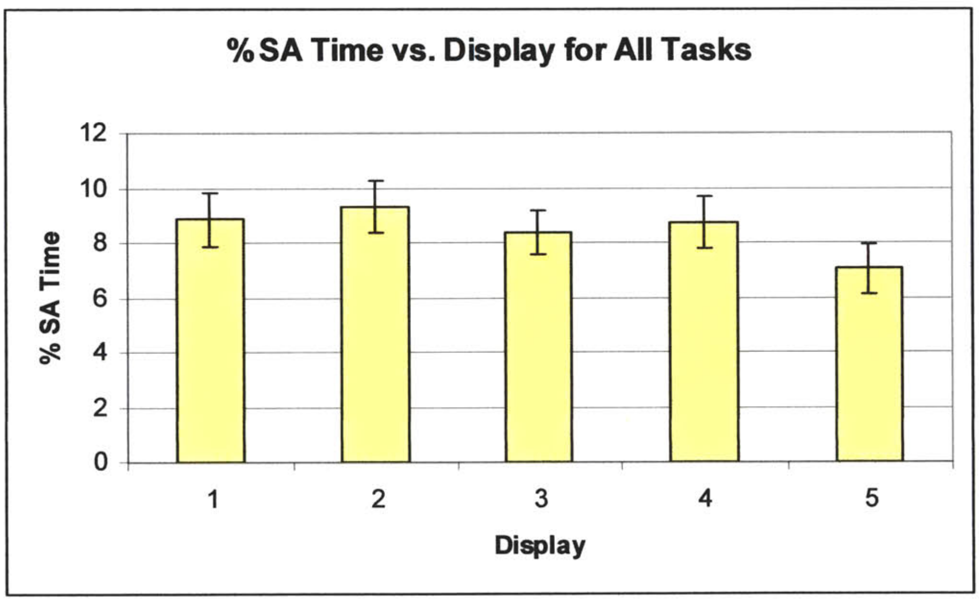


Figure 7.13 Mean % SA time versus display for both tasks

Table 7.2 SA Time vs. Task

Task	*n*	*Mean SA Time*	*Variance*	*F*	*P-value*
Handrail	80	3.625	7.731013	2.933256	0.088734
Drill	80	4.475	11.97405		

Table 7.3 lists the statistical results of the mean SA time comparison between display cases and the control display (no display). Table 7.4 likewise lists the display comparison data for the percentage SA time.

Table 7.3 Mean SA Time vs. Display for Both Tasks

Control vs. Body Only

Display	*n*	*Mean SA Time*	*Variance*	*F*	*P-value*
4	32	4.1875	6.673387	0.014645	0.90407
1	32	4.28125	12.53125		

Control vs. Wrist Only

Display	*n*	*Mean SA Time*	*Variance*	*F*	*P-value*
4	32	4.1875	6.673387	0.213174	0.645934
2	31	4.580645	16.31828		

Control vs. Both Displays

Display	*n*	*Mean SA Time*	*Variance*	*F*	*P-value*
4	32	4.1875	6.673387	0.669964	0.416199
3	32	3.71875	3.821573		

Control vs. Body + Voice

Display	*n*	*Mean SA Time*	*Variance*	*F*	*P-value*
4	32	4.1875	6.673387	0.568228	0.453817
5	32	3.625	11.14516		

Table 7.4 Mean % SA Time vs. Display for Both Tasks

Control vs. Body Only

Display	*n*	*Mean % SA Time*	*Variance*	*F*	*P-value*
4	32	8.740428	27.7819	0.008002	0.929013
1	31	8.862067	30.49135		

Control vs. Wrist Only

Display	*n*	*Mean % SA Time*	*Variance*	*F*	*P-value*
4	32	8.740428	27.7819	0.180167	0.672748
2	30	9.313004	28.59598		

Control vs. Both Displays

Display	*n*	*Mean % SA Time*	*Variance*	*F*	*P-value*
4	32	8.740428	27.7819	0.101243	0.751412
3	32	8.348892	20.67209		

Control vs. Body + Voice Display

Display	*n*	*Mean % SA Time*	*Variance*	*F*	*P-value*
4	32	8.740428	27.7819	1.746994	0.191035
5	33	7.026827	26.84749		

Table 7.5 lists the percentage SA time for both tasks. Notice that they are approximately equal at 8.2%, a reduction from the 10% value in the previous iteration.

Table 7.5 % SA Time for each task

%SA Time

Task	*n*	*Mean*	*Variance*	*F*	*P-value*
A	79	**8.219056**	19.45538	0.004917	0.944186
B	80	**8.163969**	29.54285		

7.5.4 Basis Movements Effects

The time each subject devoted to each of the three basis movements was tabulated, in addition to the time spent solely on SA. Grasping, gross position motion and fine position motion time was calculated from the recorder and video data. The percentage of time spent on each of these three movements as a function of task (A or B) is shown in Figures 7.14 thru 7.19, respectively. The time spent on SA was measured in a manner similar to the pilot study. The recorder and video data was used to determine when the subject was simply scanning the worksite or determining the correct path or tool alignment. Although it is assumed that the subjects were continually obtaining and maintaining SA, particularly during transitions, grasping and movement tasks, this SA percentage time is time where the subject was solely gaining SA - not in conjunction with any other motion - as this could not be discerned from such data. The black data points (circles) are, for each subject, percentage times for each trial and the red data points (squares) show the average for each subject. Noted on the graph as well is the average percentage time for that movement for all subjects.

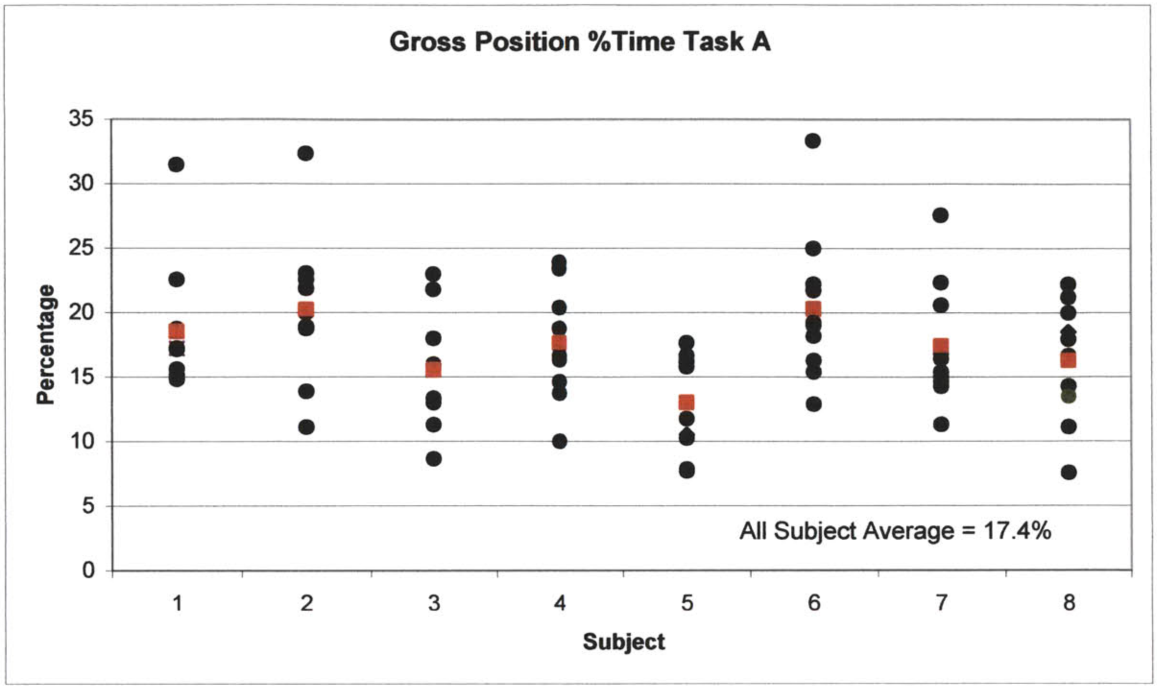


Figure 7.14 Gross position percentage time for task A

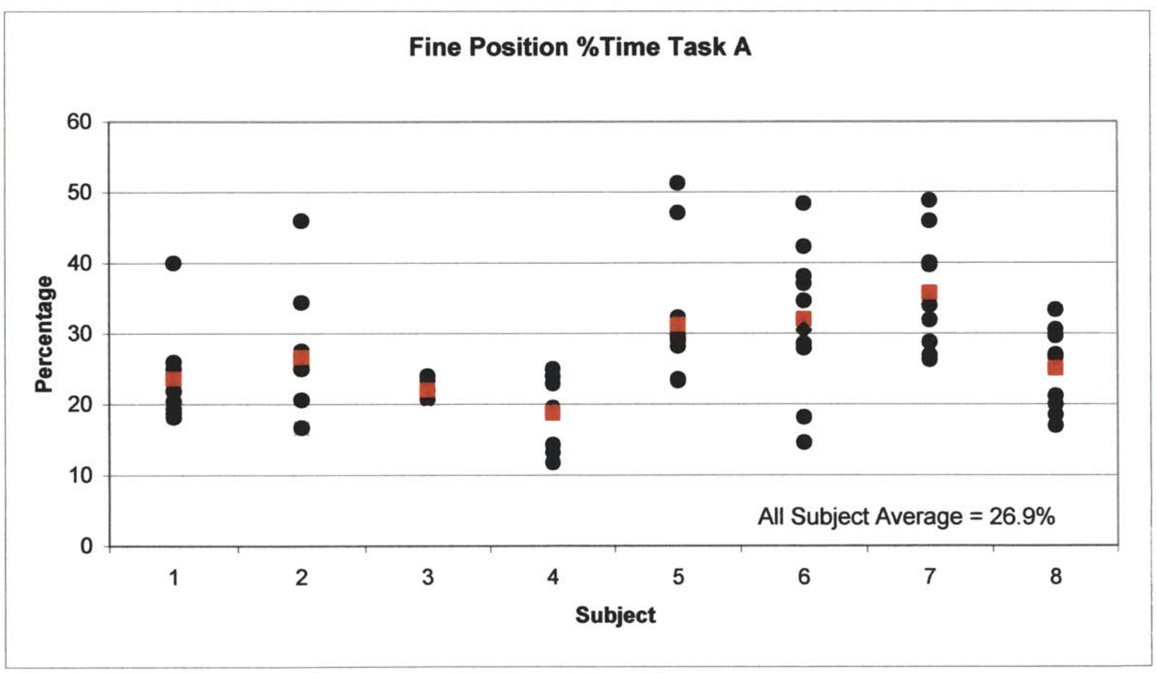


Figure 7.15 Fine position percentage time for task A

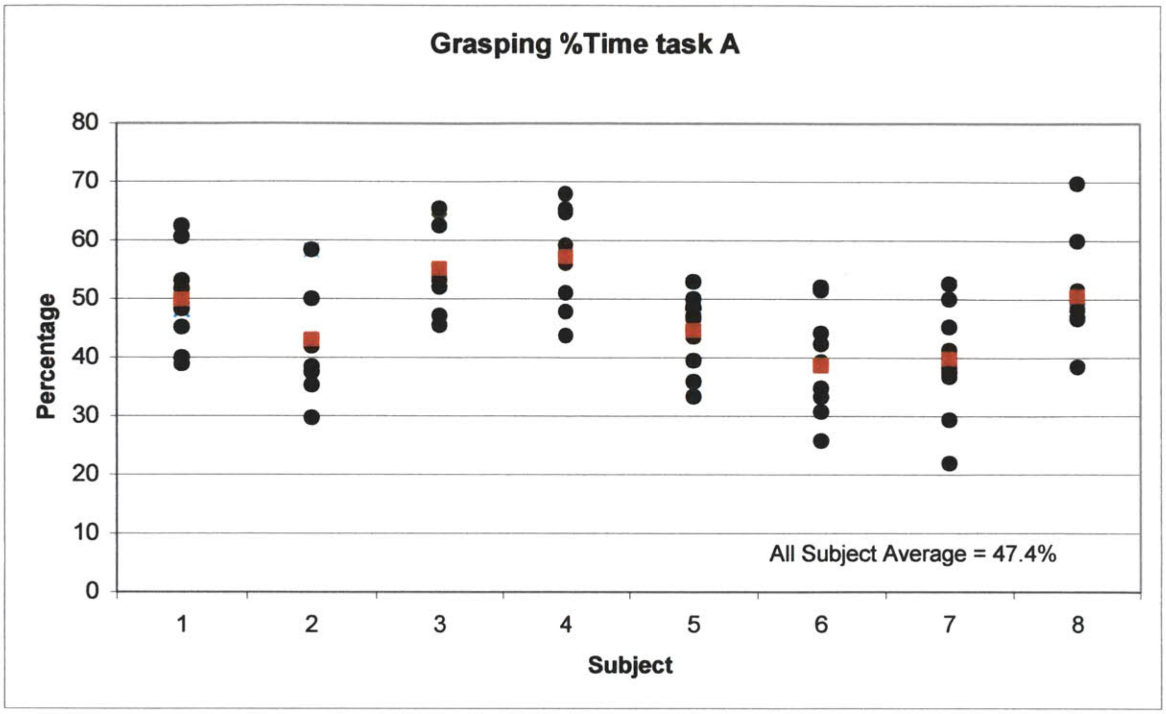


Figure 7.16 Grasping percentage time for task A

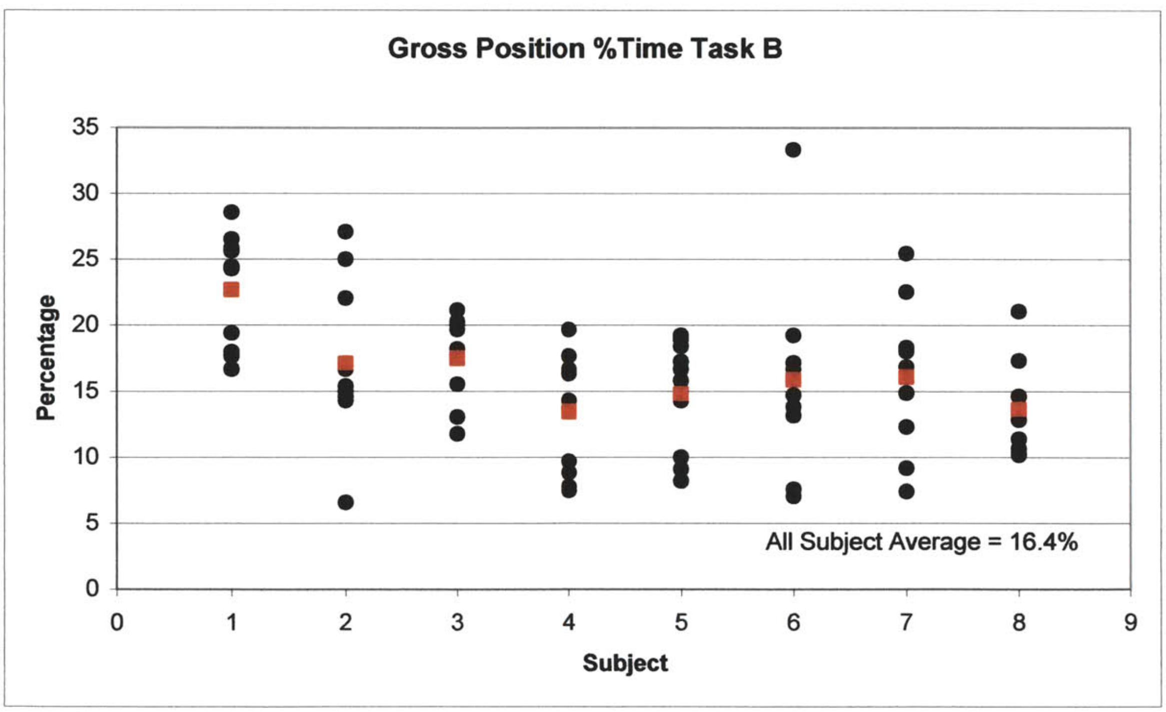


Figure 7.17 Gross position percentage time for task B

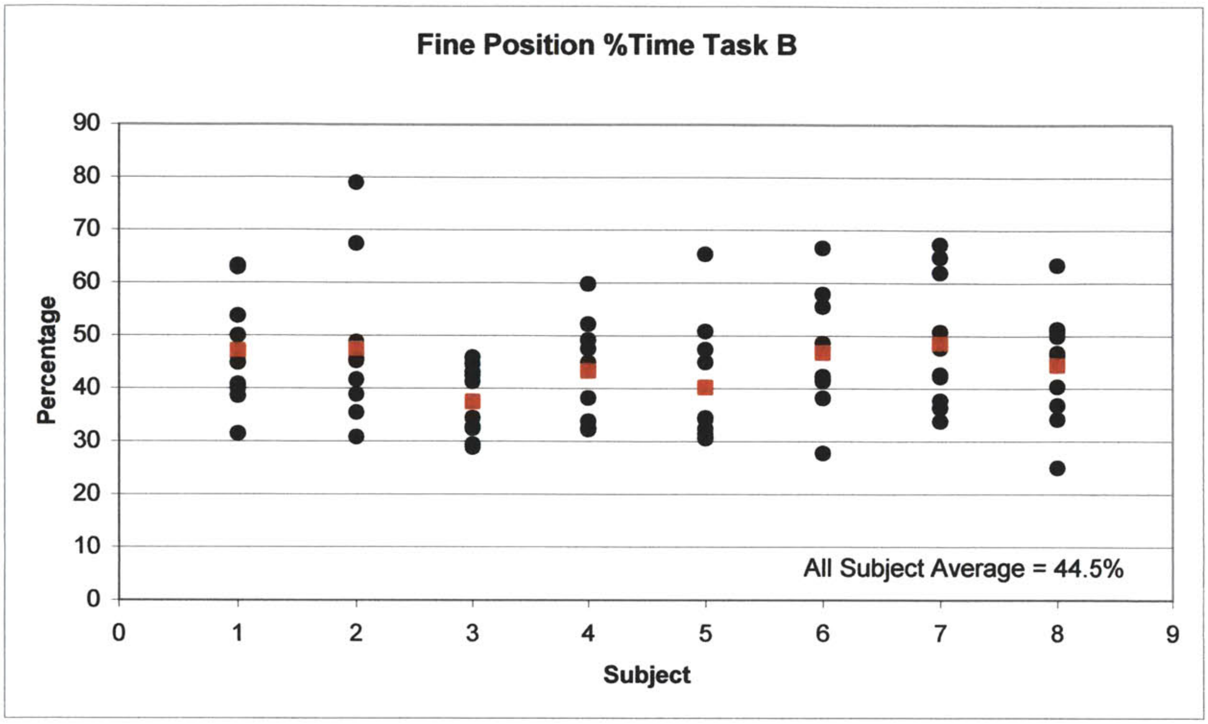


Figure 7.18 Fine position percentage time for task B

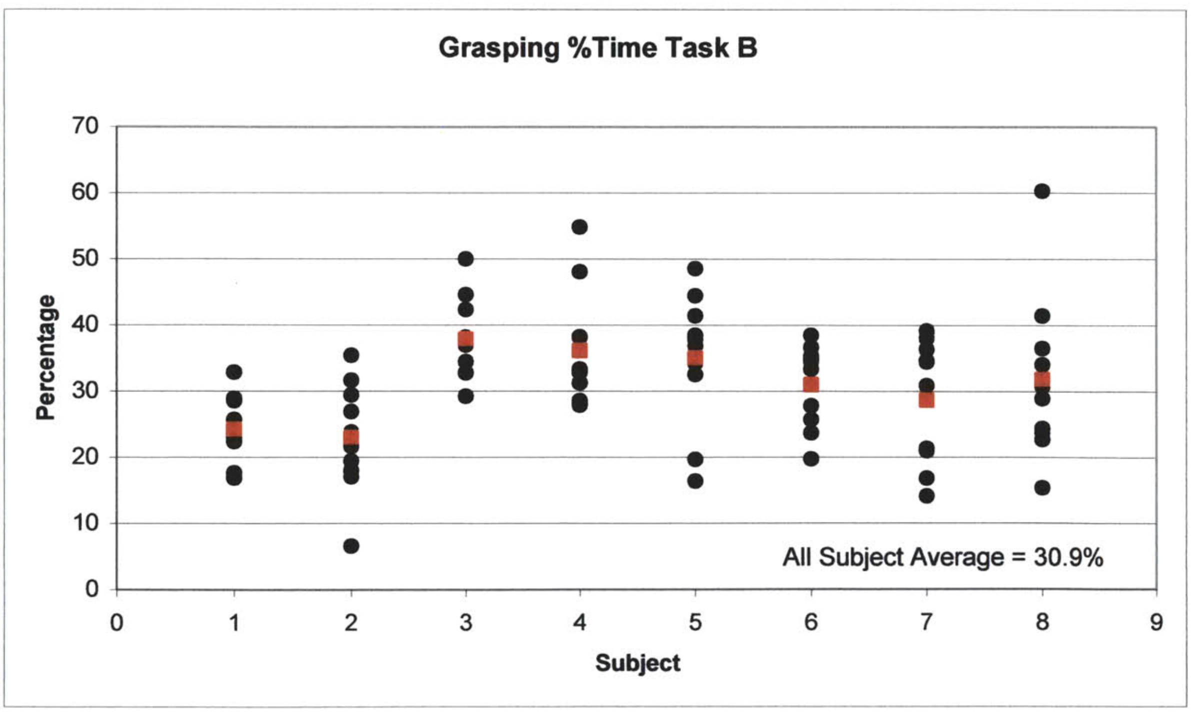


Figure 7.19 Grasping percentage time for task B

Figures 7.20 and 7.21 show the time spent on situation awareness during task A and B for each subject. Again, the all-subject average is indicated. For task A, the mean SA time for all subjects is 8.16% (variance = 19.45) and for Task B is 8.21% (variance = 29.54). Recall the mean SA time from the pilot study was 10% across all subjects.

Figure 7.20 Percentage of SA time for task A

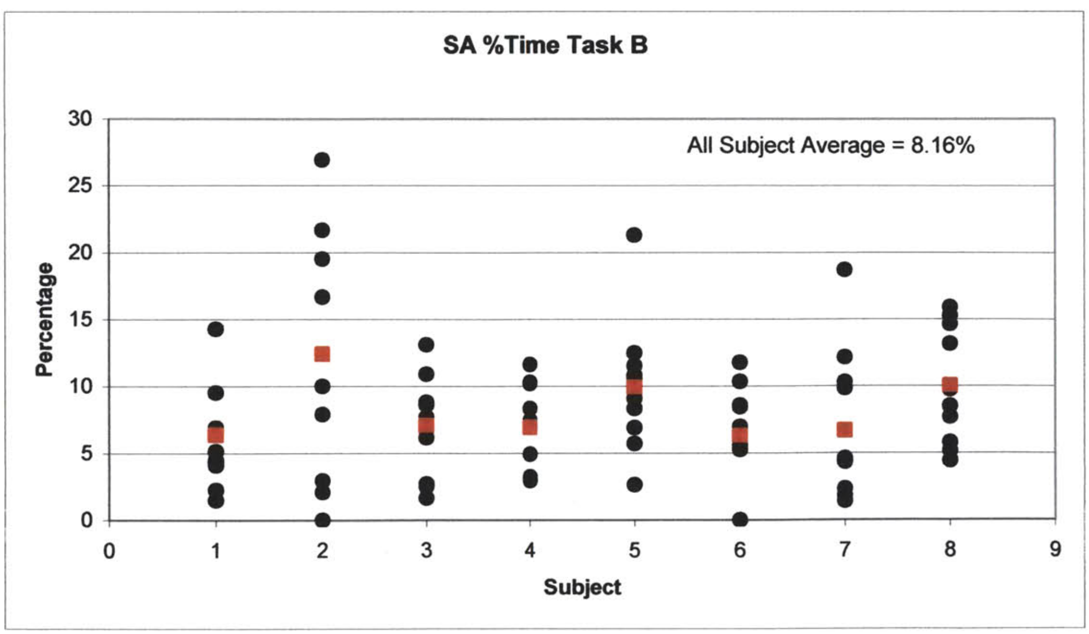


Figure 7.21 Percentage of SA time for task B

Tables 7.6 and 7.7 show the numerical averages for the above graphs along with the variances for each subject for the handrail and drill tasks, respectively.

Table 7.6 Subject mean and variance for each movement class for the handrail task

Subject	Value	Gross Pos.	Fine Pos.	Grasping	SA
1	Mean Variance	18.56541 25.72495	23.77338 40.10164	49.84294 59.38911	7.818272 15.52038
2	Mean Variance	20.28383 36.32528	47.4378 218.2309	26.608 84.03791	9.671093 14.71183
3	Mean Variance	15.56427 19.92328	37.52687 43.36628	21.94309 2.571096	7.365043 8.754119
4	Mean Variance	17.66962 18.70803	43.42596 84.56234	18.80345 25.63638	6.307824 20.43062
5	Mean Variance	13.05313 14.76273	40.25217 134.7508	31.21767 106.5927	11.12953 45.55852
6	Mean Variance	20.33218 33.32811	46.81363 123.1021	32.01208 107.7098	8.530836 24.52612
7	Mean Variance	17.45064 22.81038	48.5327 151.3686	35.75226 59.9752	6.965543 14.43051
8	Mean Variance	16.30258 21.78051	44.51141 116.4248	25.05907 30.78128	8.109508 7.880629

Table 7.7 Subject mean and variance for each movement class for the drill task

Subject	Value	Gross Pos.	Fine Pos.	Grasping	SA
1	Mean Variance	22.70295 8.7176	47.16857 108.5871	24.2221 24.79139	5.906369 14.05851
2	Mean Variance	17.1299 36.12309	47.4378 218.2309	22.99685 70.09605	12.43545 84.38787
3	Mean Variance	17.51363 9.936171	37.52687 43.36628	37.87431 39.0643	7.085192 14.45271
4	Mean Variance	13.46773 20.89873	43.42596 84.56234	36.16086 80.90625	6.945447 10.47313
5	Mean Variance	14.78416 17.7369	40.25217 134.7508	35.0283 102.9587	9.935372 24.81729
6	Mean Variance	15.89276 53.15861	46.81363 123.1021	30.99484 39.77256	6.298773 15.28145
7	Mean Variance	16.10716 30.85484	48.5327 151.3686	28.67736 88.46082	6.682785 33.96244
8	Mean Variance	13.63762 12.05672	44.51141 116.4248	31.82861 157.0887	10.02236 19.38136

The above figures give a visual indication of the individual subject and task variances for the different basis movements within the integrated task. Particularly, the variance of the mean for each basis movement can be seen across all subjects relative to the total task time. Note the consistency in the time subjects spent on each of the movements for the handrail and drill tasks.

7.5.5 Learning Effects

Learning curves for each subject are illustrated in Figures 7.22 and 7.23. Subjects 1,2,6 and 7 show steep learning between the first and second trials for the handrail task. Subject 7 also showed a spike in task time for trial number 4, the first trial for this subject in the "no display" condition. In handrail trial number 9 for subject 3 a spike in task time is traced to a problem with the middle robot finger when the distal joint failed. The subject attempted to grab the handrail from underneath with the fingers flat, however the distal middle finger joint would not extend and therefore the subject could not fit the hand under the bar until the second attempt. During the drill trials, subject 7 exhibited a spike in task time during the third drill trial. In this trial, the drill was dropped and recovered, however the subject's mapping changed as the drill was replaced, increasing the remaining task time. In the ninth drill task for subject 1 the drill grasp was not strong. As a result there was difficulty replacing the drill into the socket, as the maneuver required a great deal of wrist pitch. Likewise, subject 4 in their ninth drill trial had a poor grasp increasing the socket placement time. In subject 4's final trial, a re-try of the insertion after a missed first attempt added to the task time.

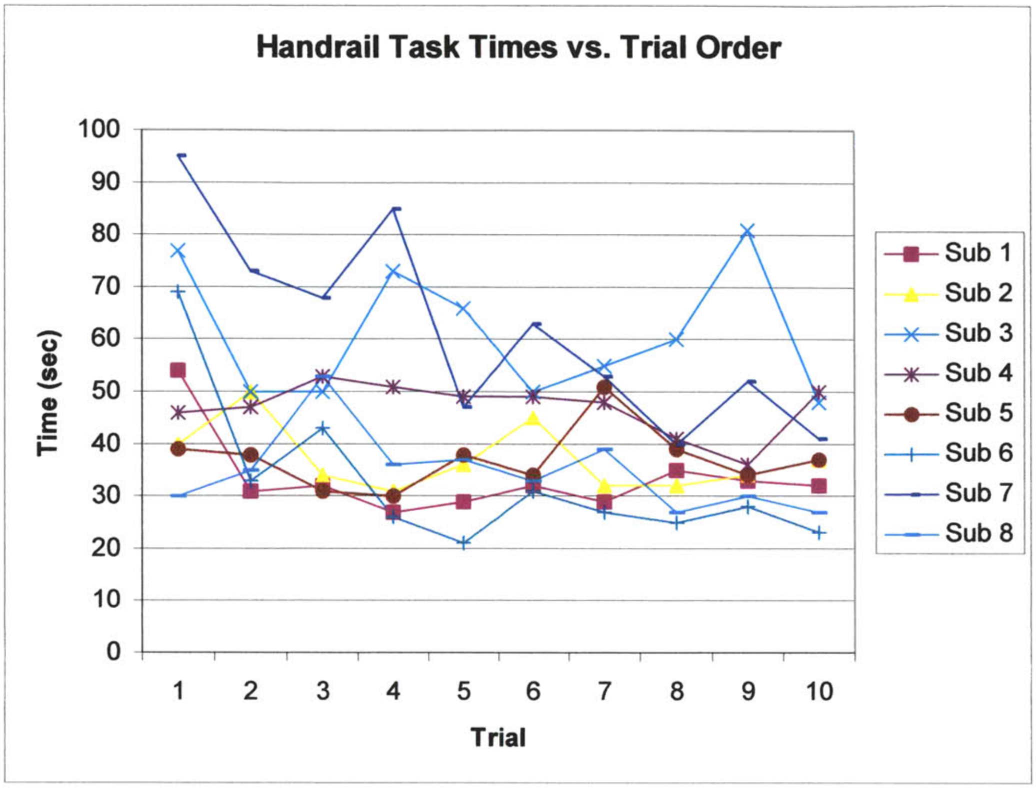


Figure 7.22 Handrail task learning for all subjects

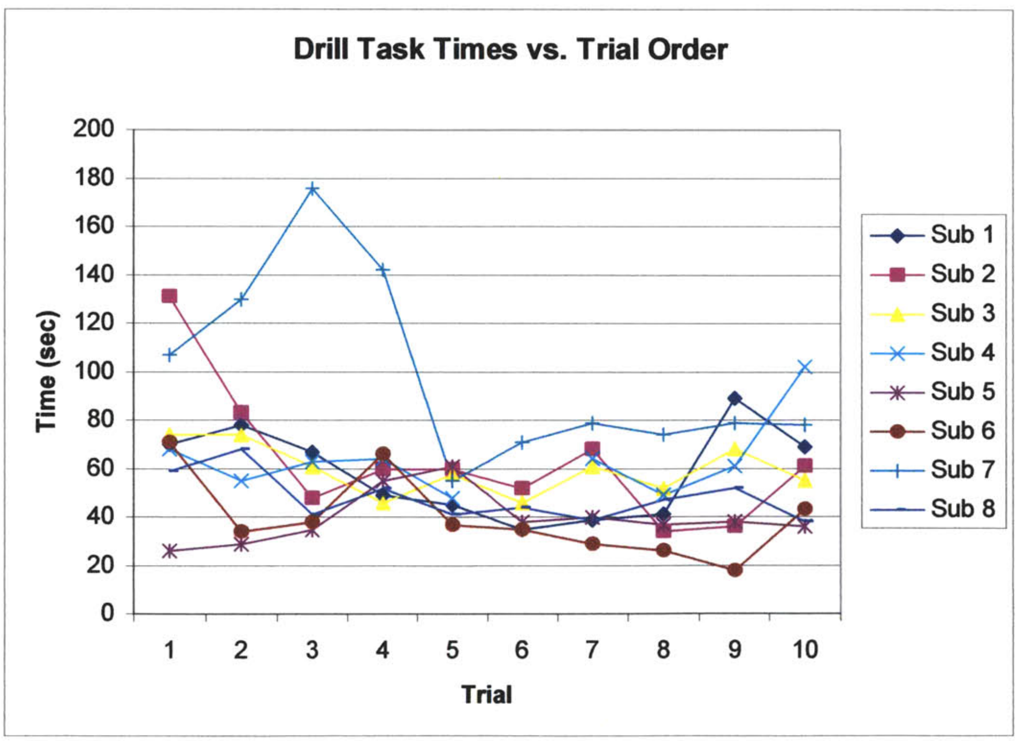


Figure 7.23 Drill task learning for all subjects

7.6 Discussion

The effect of the display on the number of errors indicates that the level of workload with the presence of both displays was not taxing – in fact the number of errors was lowest in this case. However, the task time did not improve significantly across the display cases. This indicates that the vision system in place (Robonaut cameras and HMD) is sufficient to perform the task. If the vision system was lacking somewhat to the extent that the displays alleviated any deficiency in the system, one might expect that the task time to improve with the addition of a display. In this set of tests, there was an experimenter always present to warn the subjects in the case of a dangerous collision with the outside and therefore at the outset, subjects did not develop the scan pattern witnessed in previous studies. Without adopting the scanning as a baseline behavior, it could never be affected by the presence of a display. Subjects knew and counted on the fact that someone would warn them if any real harm was about to befall the hardware from external sources, therefore they freed themselves of this time consuming monitoring and concentrated more on the task. However, the body display did give the subjects much needed information about their own body position in order to avoid reach limits and self-collisions. Almost all subjects remarked that they "missed" the body display when it was removed from the HMD.

Although task time did not show a significant improvement for a particular display, the display did affect the variance in task times. Subject variances for task times were lower for display 2 (body only) for both tasks A and B independently and overall. Indeed the mean task time for display 2 was the lowest (although not statistically significantly). Likewise display 3 showed slightly higher variances although lower than displays 1, 4, and 5. Displays 1 and 4 did not have the body shown in the visual field. Display 5 did show the body but it also included auditory cues that may have added to the workload for many subjects. The benefit is that one can better predict subject performance where low variances are exhibited (as they will tend to behave consistently). Another effect of the displays was to decrease the number of errors and consequently, mitigate stress on the robot hardware and increase task performance.

During the research phase of the pilot experiment, it was noted that the subjects spent a great deal of time scanning their body for a sense of its position and orientation relative to objects in the workspace. It was thought that some of that time could be alleviated with a display that indicated the operator's body position (which could not be seen through the robot eyes beyond the hands and a section of the forearm). The integrated task time was therefore separated into four elements – the basis movements and SA time. Results were obtained for the percentage of task time subjects spend doing gross positioning, fine positioning, and grasping maneuvers, as well as the percentage of time obtaining and maintaining SA. The two tasks were designed to have a grasp-transfer-fine position-grasp flow to the basis movements. The handrail task time was concentrated on the initial handrail grasp (47.4%). This is expected due to the nature of the precise hand position required to grasp the particular handrail shape. The gross position percentages for the two tasks were roughly equal (17.4% for task A and 16.4% for task B) as the gross position movement was designed to use the outer envelope of the robot reach limit. The drill task was predominantly a fine positioning task during the drill-in-hole alignment phase (44.5%). This measurement again validates the basis task classification.

It is when examining the results of the SA time (percentage of total task time that is spent obtaining or maintaining SA) that the most interesting result emerges. Recall the pilot experiment revealed a baseline SA time of 10%. These integrated tests reduced that with the display design to an average of 8% for all subjects and all tasks. Again, that number was independent of task and trial order confirming that a minimum constant SA time is required but can be reduced. The percentage of total task time spent on SA for task A is 8.16% and 8.21% for task B. Although not a significant improvement, a certain indication that this amount of SA time could be reduced by the addition of well designed sensory feedback aids (however it is suspected that some baseline amount of pure SA time will always be present during task performance, even if it cannot be directly measured). The consistency of this time across two distinctly different tasks in both this and the pilot study also indicates that such a baseline time is required.

One might expect that more than 8% of task time should be devoted to SA, however this result is a function of three parameters. First, the number of degrees of freedom was limited in this experiment as only the right arm was utilized. If the task was dual-arm and involved torso movement, than this number may increase. Second, there was a fail-safe mode discussed earlier where the subject knew that before any real harm would come to the robot an experimenter would alert them. This would reduce their need for SA as well. Finally, time spent on SA while accomplishing another part of the task could not be measured directly and if included in the calculation, may also lead to an increase in that percentage.

Given the above results, a new display was designed to more directly affect subject task performance and number of errors. As part of the proposed methodology, it was also desired to test the re-design using Robosim with both experienced and inexperienced operators. Several of the subjective comments regarding the displays noted that they lacked immediate information regarding the dangerous orientation. Although the displays were in the upper half of their view, most subjects concentrated their focus to the lower part of the screen and did not often scan the top of the screen for display information. This contributes to the lack of significant effect of the display on task time, as some subjects ignored the displays entirely. Likewise, when the auditory danger warnings were given, subjects felt that they lacked information content. That is to say, the subjects wanted a very descriptive explanation of the warning. Rather than "collision alert", hearing that the forearm was about to hit the torso would have specified exactly the limbs involved and permitted faster correction times. The displays designed in the subsequent experiment gave a more immediate indication that a problem existed, as well as the precise nature of the problem.

7.7 Design Implications

The percentage of task time spent on SA was calculated to be 8% for these integrated tests. This confirms the presence of the baseline amount of SA subjects need for task performance that was first observed during the DART integrated studies. Although the displays reduced this time from 10% to 8%, the total task time was not reduced. The body display in particular did not show a statistically significant effect on the task time however subjective comments indicated that they "missed" the body overlay when it was not present. A drawback to the display indicated by subjective responses was the need to shift one's gaze away from the primary task in order to view it. For the third design iteration the aim was to reduce overall task time. A second objective was to provide intuitive and immediate warning information without detracting from the primary task.

8 Display Design Iteration III

Even if you're on the right track, you'll get run over if you just sit there

-Will Rogers

8.1 System Issues and Requirements

A new display was designed to increase performance without increasing operator workload. The requirements for the display and experiment are listed below:

- Provide more immediate indication of error without requiring gaze shift away from primary task
- Remove "safety net" of experimenter cues in order to increase subjects' reliance on display for error information
- Combat excessive elbow height and self-collision – the two most common warnings from previous experiment
- Utilize simulation tool to evaluate display design

8.2 Simulation Tasks

For this session of simulation experiments, seven out of eight of the previous subjects participated (four males and three females) and four novice subjects were recruited to participate (four males ranging in age from 23 to 39). The identical hardware setup to the previous simulation trials was used in this experiment - two laptops, HMD, and Polhemus trackers. The following sections describe the tasks, displays and protocol. The results are presented in section 8.3 and the discussion in section 8.4. Simulation trials for this experiment involved positioning the virtual robot hand over a virtual handrail. Figure 8.1 shows several views of the virtual environment.

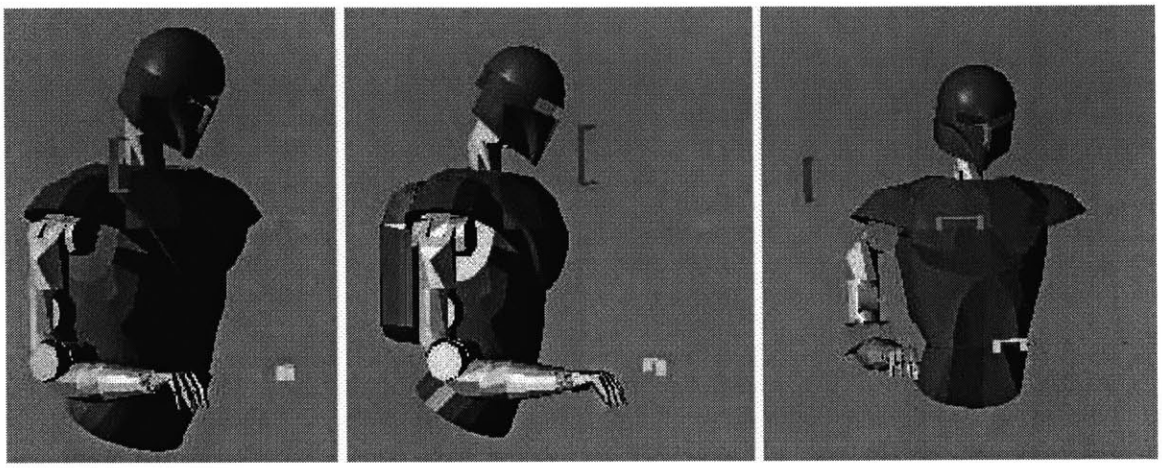


Figure 8.1 Views of the virtual task environment

Three handrails were used in the scene in various locations and orientations. Starting from the home position with the palm facing down in this case (as opposed to the palm facing upwards in the integrated trials home position), the subject translated the arm and hand to the handrail and position with the hand over it as if they were going to grasp it. The yellow handrail is low relative to the torso and positioned at a 30degree angle to the horizontal, much like the physical handrail from the integrated tasks. A white handrail was positioned at approximately chest level in a horizontal orientation, and a green handrail was up and to the right of the robot and is oriented vertically. Subjects were instructed to place the hand over the handrail as accurately as possible while keeping in mind the state of the robot. Subjects were also told to keep in mind the three cautionary conditions discussed in Chapter 4, excessive wrist pitch, chicken winging and self-collision, and commanding the robot to those states. This was aided by a display discussed in the following section. The hand was fixed in a cupped position so that the CyberGlove was not necessary. Subjects were seated in front of the laptops and Polhemus transmitter wearing an HMD, chest sensor and POR sensor. Figure 8.2 shows a photograph of one of the subjects performing the green handrail task and figure 8.3 shows a close-up of the hand grasping the handrail. Notice that the subject must place the handrail between the thumb and the fingers.

Figure 8.2 Photograph of subject performing green handrail task

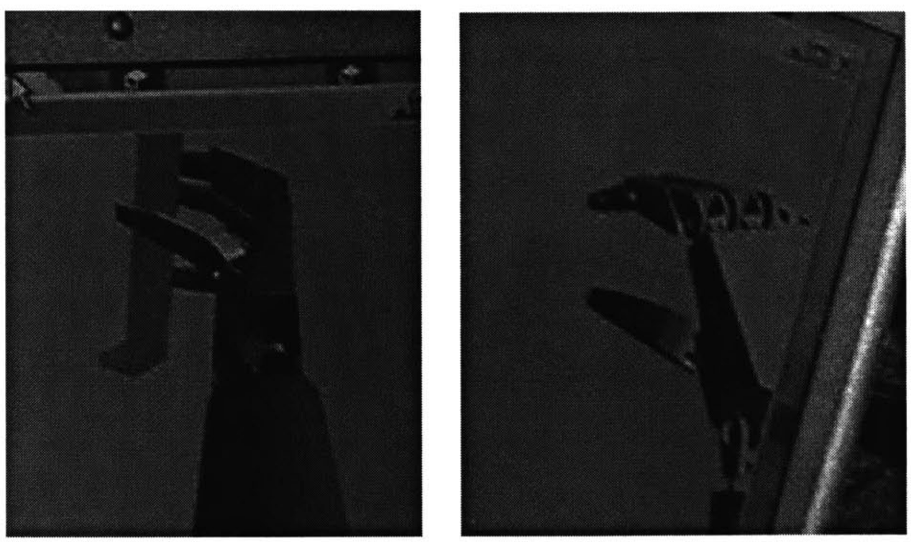


Figure 8.3 Close-up views of hand positioned over handrails during subject trials

Given that the task was done in a virtual environment and that there were no contact forces modeled, there was no penalty for colliding or passing through objects in the simulation. Subjects were therefore instructed not to pass the hand through any of the objects in the scene in order to reach their target during gross position movements.

However, they were also instructed to pass a part of the palm through the handrail in the final grasp state to ensure that they were indeed over the target and confirm the depth perception, then retract the hand to the final position.

8.2.1 Displays

As mentioned in the previous section, subjects were told to avoid putting the virtual robot in any of the three cautionary positions. Two displays were designed to aid the operator in determining if the robot was in a harmful state. As the wrist was always in view and could be constantly corrected, the self-collision and chicken wing alerts were chosen for the displays. Subjective comments expressed that when the wrist overlay was present it was often ignored since a good view of the wrist was available at all times. The self-collision and excessive elbow height, on the other hand, were virtually impossible to detect without some additional information. Subjects also commented that they tried to minimize the number of times their gaze was removed from the task they were concentrating on, even if it meant receiving status information on the robot. This led to the creation of a display that changed the color of the virtual robot palm to reflect the type of error the subject was committing. If the subject was in danger of a self-collision, the palm turned red. For excessive elbow height, the palm was colored blue. This allowed the subject to be alerted to the problem even when focused on the primary task of reaching the handrail, without requiring a shift of gaze to another part of the visual scene.

To determine when these limits were hit, a dynamic link library (.dll) file was written and "attached" to the simulation. The simulation code was set up such that if a .dll file is present, it will do the functions outlined in the .dll at every cycle before continuing. In essence, .dll files are "back doors" to the simulation, so that environments can be manipulated without needing direct access to the simulation source code. In this case the .dll (found in Appendix M) contained code that overwrote the simulation drawing routine. Instead, the .dll drawing routine contained limit checks, model color changing commands and data output file commands. Each of the two displays will be discussed in further detail in the following sections.

8.2.1.1 Elbow Position Display

This display was designed to mitigate excessive elbow height (chicken winging) on the robot arm. This could be measured in a variety of ways. For this experiment, the x, y, z position of the chest (relative to the transmitter) was used as the reference frame to determine if the elbow joint was positioned too high in the z-direction. To calibrate this, the arm was placed in a position where an alert would be given if Robonaut were in operation, and the z position of the elbow measured. The positive z direction was measured downward from the head to the tail. If the elbow crossed that z-plane limit, the hand changed to blue (see Figure 8.4).

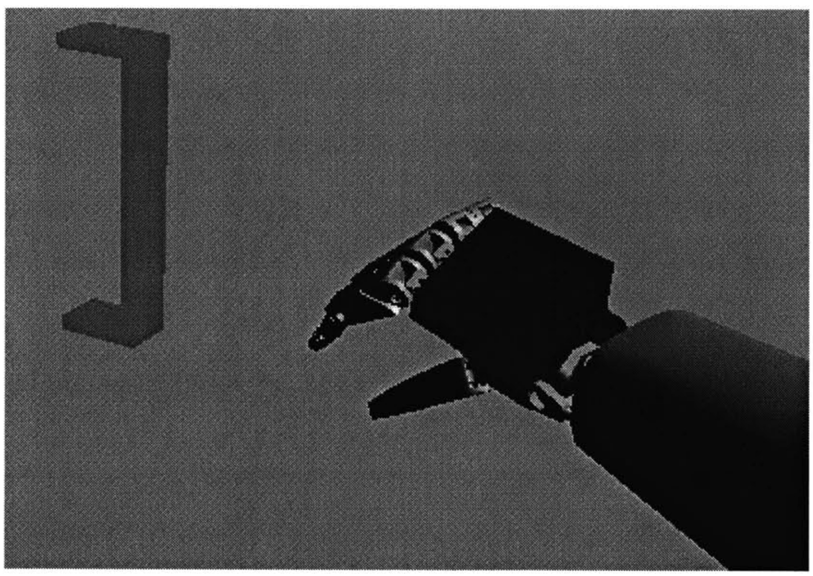


Figure 8.4 View from subject's perspective of blue joint warning

The .dll file retrieves model data for the right elbow and right palm. The position and orientation matrix for the elbow was called and the row and column element corresponding to the z value of the elbow was tested against the predetermined value. If that value was exceeded, the right palm model color value was altered and the scene drawn.

8.2.1.2 Arm and Elbow Collision Display

This display alerted the subject if any part of their arm was in danger of colliding with the torso. In Enigma, the user has the ability to define collision models. That is to say, Enigma can calculate the minimum distance between one model and any other model in a structure. In the graphical interface you can specify for each model, which models you would like to test for collision. For this experiment a hidden cylinder is drawn within the torso that gives a margin for collision warning as opposed to collision occurrence (see Figure 8.5).

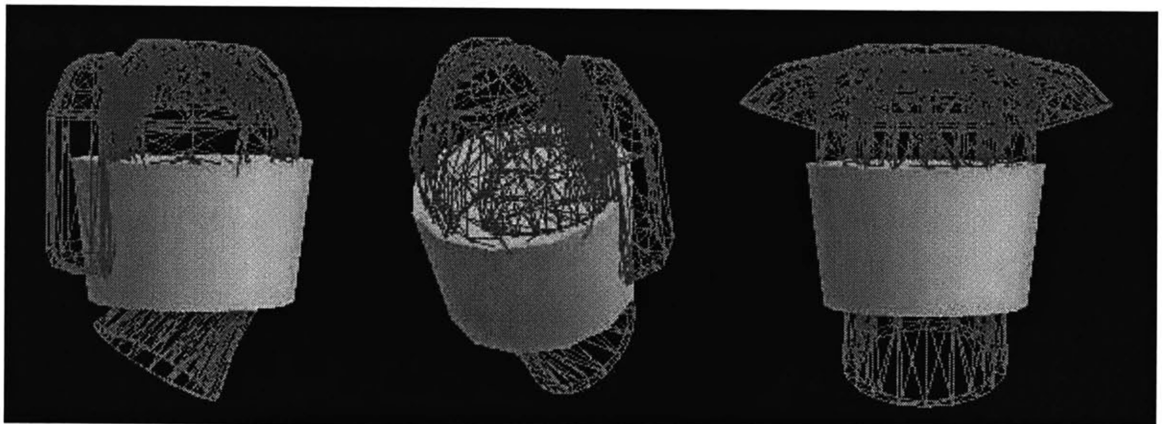


Figure 8.5 Collision model for the simulation experiments shown in green with the Robonaut torso grid overlaid for comparison

The program was set to check for collisions between this cylinder, and the elbow or forearm. The .dll file called the models needed, calculated the minimum distance using and Enigma function call, checked to see if it is within a specified tolerances, then changed the hand color if necessary, to red (see Figure 8.6). Since the collision cylinder was wider than the torso, if the minimum distance between the elbow and cylinder was zero, then a collision was imminent. During pilot study trials, a similar display was constructed to indicate collision. In that study, the entire task environment was modeled to test for external collisions (as opposed to internal collisions here), and three levels of warning given to the subject (yellow, orange and red in order of severity and proximity to another object). Subjectively, it was reported that the yellow and orange displays were ignored, and only the red taken seriously by the users. Subjects felt that they were alerted too early and that the robot was in no real danger, therefore they waited until the condition was serious before breaking away from primary task performance to change their robot body position. In addition, due to a time lag in the system, the data was often erroneous and instead subjects used the display more as a body position awareness tool than as a collision avoidance tool. Learning from previous work, only one warning state was chosen here, and the color red used to indicate a "hit". The blue color was used to indicate an undesirable position rather than an imminent danger.

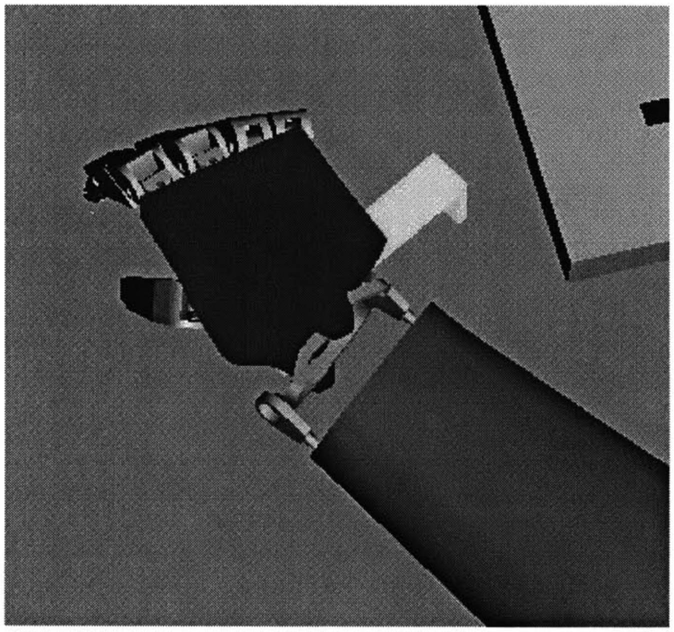


Figure 8.6 View from subject's perspective of red collision warning

The yellow handrail was placed such that the red collision warning might be activated if the subject does not maneuver carefully to the handrail. The green rail was designed to elicit the blue warning as it is near the high elbow position. Subjects must learn the proper arm motions to approach the handrail so as to not set off the display. The white handrail was designed to act as a neutral position rail in the center of the chest at chest height.

8.3 Protocol

There were two display conditions, display on and display off. At the beginning of each trial the subject was told whether the display was on or off. They were instructed to keep the robot away from the limiting conditions in both cases. With three handrails and two display cases there were six combinations of display and handrail color. Each combination was performed four times for a total of 24 trials in one session lasting approximately 60 minutes. The trial began with the arm in the home position. The experimenter then told the subject which handrail was the target and the subject maneuvered his/her hand to the target. Once positioned carefully over the handrail, the simulation was frozen and the subject rests for approximately 60 seconds while the next trial is prepared. Novice subjects were given practice time with the simulation for approximately five minutes before beginning data collection. Data recorded include trial time, elbow z position, and minimum distances for both elbow and forearm segments. Video was also recorded of each trial.

If it was a "display on" trial and it is activated during the run, the subject must move the arm into a safe position and clear the display (with the hand in position over the rail) before the trial can end. The experimenter would also inform the subject if they needed to correct for wrist pitch. The first time the display was activated for each subject, verbal cues were given to aid him or her in correcting their pose. If the subject had difficulty correcting their pose they could return to the home position and retry, or else freeze and re-index if necessary. The trial was not however, restarted, even though they could return to the home position during the session. During display off trials, subjects were told to remain aware of the robot position although there would be no indication if the limits had been exceeded unless the subject looked around his/her environment and made note of where the robot limbs were located. A subjective questionnaire was administered at the end of the session.

8.4 Results

As discussed in Chapter 4 section 5, Robonaut Command and Control, if a subject commands Robonaut (or Robosim) to travel beyond its reach limit, the robot/sim will not comply and will instead slew to a position within its capability. This can cause operator error (due to mode awareness) if the operator is not aware that this internal robot/sim limit exists. Another mode awareness issue surfaces with the Polhemus as was evident during the KC-135 trials. If the Polhemus sensor is placed beyond its range, the sensor reading will be incorrect, therefore the commanded position the robot/sim is trying to attain will not be what the operator intended. A third mode awareness problem occurs if the operator commands the robot/sim to move too quickly. In this instance, due to the rate limits, the robot/sim cannot "keep up" with the command and the actual position will lag the commanded position. The operator will perceive this lag as the system catches up. If the operator does not input further commands, the robot/sim will eventually reach the commanded position and tracking can continue. If the operator continues to command the Polhemus sensor, they can drive the system into an unstable state. In the case of the simulation, the picture will often freeze as the system calculates its position and calls the drawing routines. This instability was observed several times during the handrail trials. Instances where the joint limits were reached were also observed. When the graphics froze during a trial, the subject would match the position of their human arm to the frozen graphic of the robot arm and when the sim continued drawing, the subject was re-mapped to the robot position. This time (noted as a "hold" time) varied from 3 to 30seconds and was not counted toward the total completion time of the trial. Five trials out of 264 experienced holds. In several cases, the simulation could not recover from the instability and the program would abort. Five out of the 264 (not the same 5 trials with hold occurrences) trials experienced terminal aborts. No data was re-taken for these trials.

The average task times for each subject are plotted in the following three figures. Figure 8.7 shows the average task time for the yellow handrail, while figures 8.8 and 8.9 show the white and green handrails, respectively. For the green handrail task, subjects one and 8 show higher error bars as they had significant learning from the display as will be discussed in the following section.

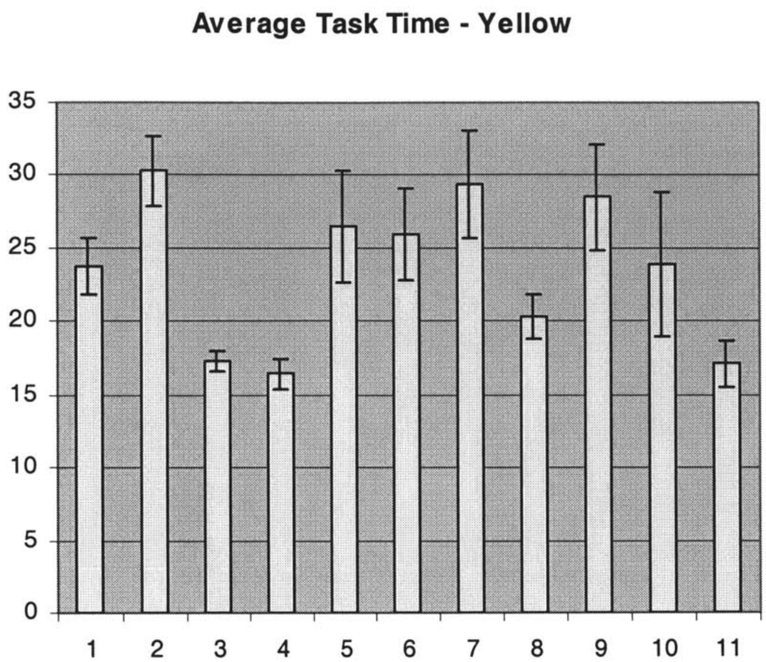


Figure 8.7 Average task times for the yellow handrail task

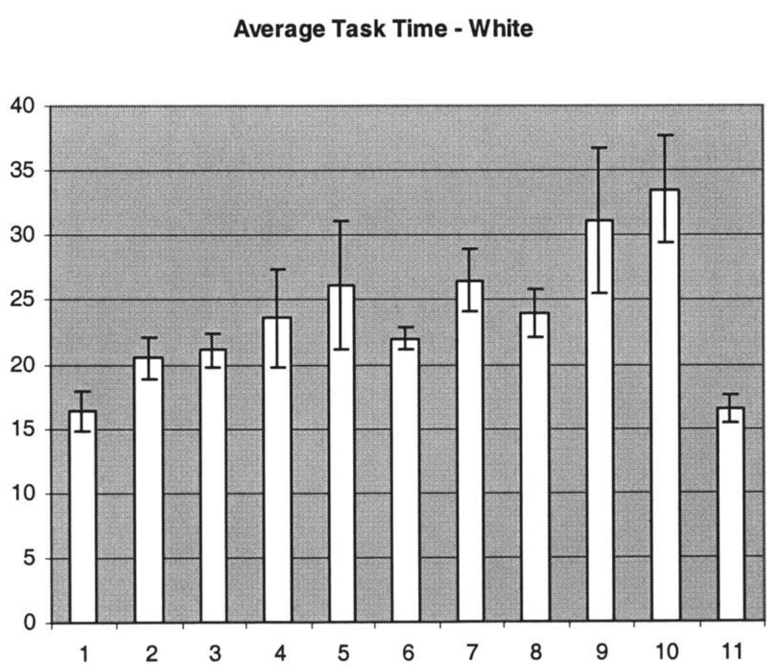


Figure 8.8 Average task times for the white handrail task

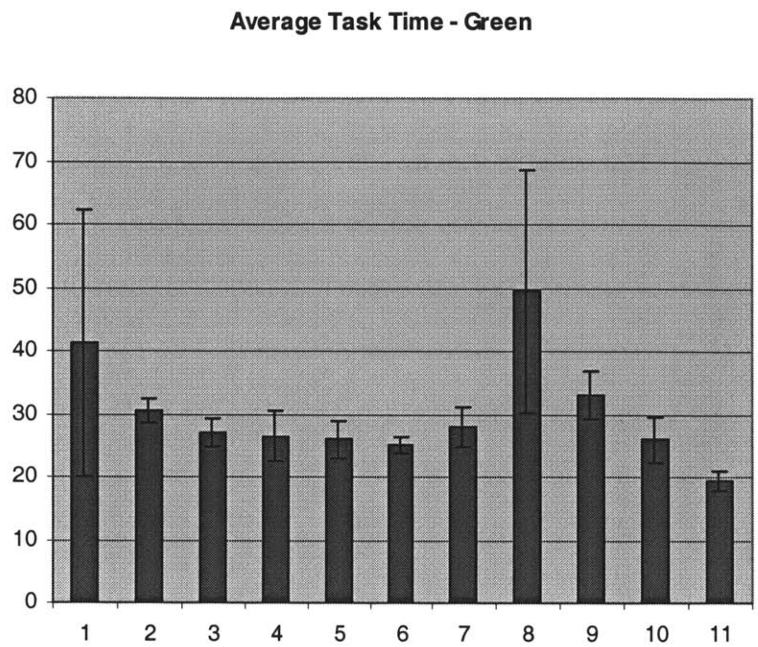


Figure 8.9 Average task times for the green handrail task

Subjects 1 thru 7 are the experienced subjects and subjects 8 thru 11 are the novice subjects. No significant difference was found between experienced and novice subjects for any of the handrail tasks. Figure 8.10 illustrates the all-subject means for each of the handrail tasks. There is a significant difference between the yellow and green handrail tasks and between the white and green handrail tasks. This result is expected as the green handrail was both the farthest from the starting position and was the most difficult to obtain without exceeding a pre-defined joint limit.

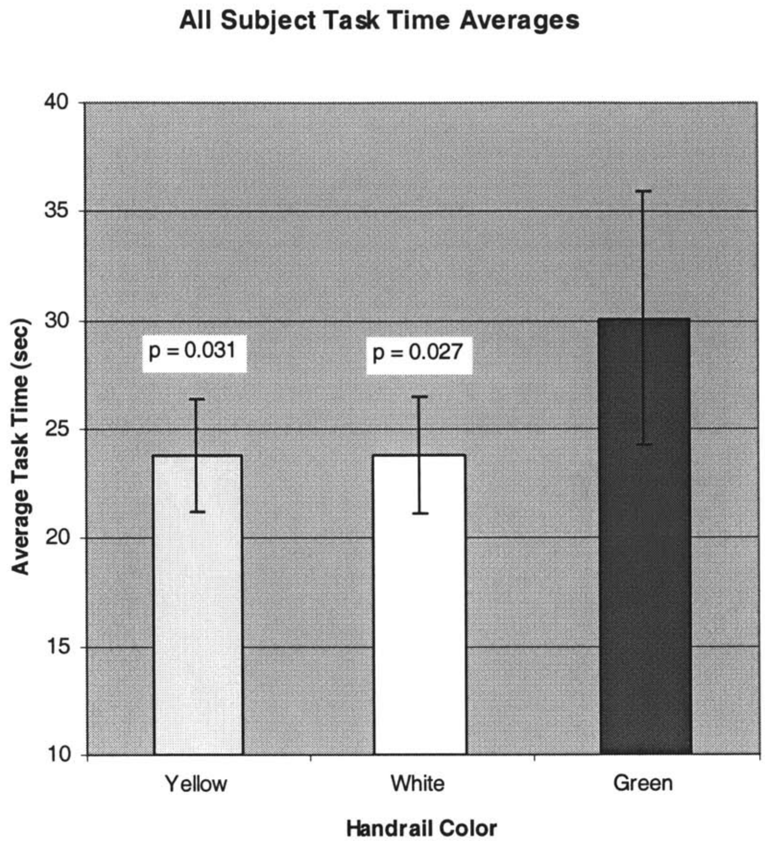


Figure 8.10 All-subject task time averages for each handrail color

In the previous integrated experiment there was a large gender difference for the robot and manual tasks, but not for the simulation trials. Likewise in this experiment, there was no significant gender difference in terms of task time or number of errors.

There were significantly higher numbers of elbow height errors than self-collision errors ($p<0.001$, $F = 39.26$). An error is recorded when the collision limit or elbow height limit is exceed – independent of whether the display is on or off. Recorded data included the minimum distance and elbow height for each trial. This output data revealed whether a limit had been exceeded during display-off trials. A total of 93 trials contained errors with 29% red display errors and 71% blue display errors. Table 8.1 lists the total numbers of errors for all trials and subjects. Subject 2 was the only participant who exhibited zero errors throughout the trials. There was in addition, significantly higher number of blue display errors for novice subjects compared to the experienced subjects ($p = 0.02$, a total of 18 for experienced and 29 for novice subjects). No experience level effect was found for red display errors (a total of 7 for experienced and 8 for novice operators).

Table 8.1 Number of errors leading to display activation for each task

Handrail Color	Elbow/Arm Collision (Red-hand warning)	Excessive Elbow Height (blue-hand warning)
Yellow	22	0
White	0	27
Green	5	39

8.4.1 Display Effects

The display showed a significant effect on subject task learning. Figures 8.11 through 8.13 show examples of subject's performance during the green handrail task with the display on, showing significant improvement (all $p < 0.05$) as the trials progressed. Note that subject 1 experienced a simulation failure, therefore Figure 8.11 only shows three display-on trial data points.

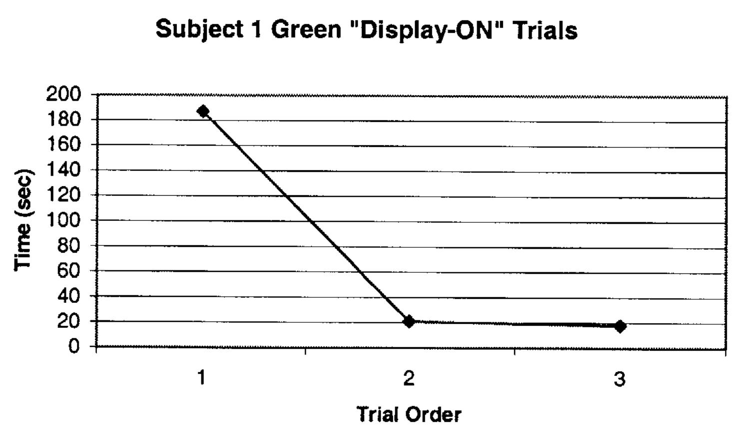


Figure 8.11 Subject 1 task time and learning trend for green handrail trials in the display-on condition

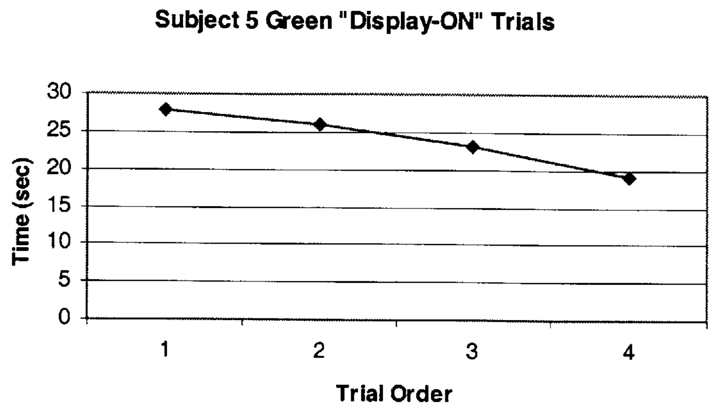


Figure 8.12 Subject 2 task time and learning trend for green handrail trials in the display-on condition

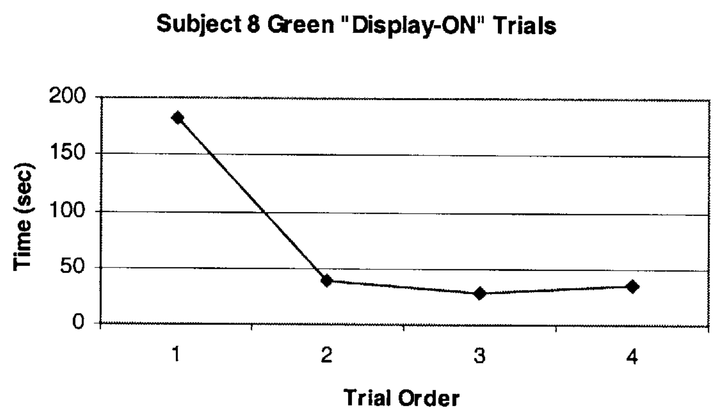


Figure 8.13 Subject 8 task time and learning trend for green handrail trials in the display-on condition

Subjects 1 and 3 show similar phenomenon. Their first trial was a display on trial and once their display was activated due to excessive elbow height, they each took roughly three minutes to learn the correct method of approaching the handrail without inducing an error. After that first lesson, subsequent trial times were significantly lower and consistent. The learning curves in these cases are primarily due to display learning. Subject 2 has a profile similar to the remaining subjects, that of a continual improvement and/or consistency of task time to within approximately five seconds over the course of the handrail trials with the display on. Subjects in this case show learning of the task over the course of the experiment. Learning trends were analyzed for all subjects to test the effect of trial order and display on performance. The overall learning effects were significant across all display and handrail cases. Table 8.2 lists the results of trial order comparisons for general learning effects. All display cases are tested together here, as the display did not directly affect task performance time over all subjects and handrail tasks. Data indicate that significant learning occurred as early as the second trial. The large variance for first trial task times is due to two subjects that had approximately 3 min trials in the first display-on condition. Task times were compared for display-on trials and display-off trials and no significant difference was found. The effect of display on task performance was also quantified and the display did indeed significantly improve task times over the course of the trials (p=0.02, F = 5.23).

Table 8.2 Effect of trial order on learning

Trial Comparisons		n	Mean	Variance	F-Ratio	P-value
1st Trials vs. 2nd Trials	1st 2nd	66 64	32.8 25.8	829.2 92.0	3.95	0.04
1st Trials vs. 3rd Trials	1st 3rd	66 64	32.8 22.9	829.2 57.2	7.08	0.008
1st Trials vs. 4th Trials	1st 4th	66 58	32.8 20.9	829.2 32.8	9.45	0.002

8.5 Discussion

This experiment confirmed several findings from Experiment A at the same time revealing the power of Robosim as a tool for display design and training platform. Average task times overall, showed low variances with the exception of subjects 1 and 8. Both of these subjects had significantly long green handrail trials with the display on. This difference for all subjects was a result of the learning process subject's experienced when correcting their arm position when the display was activated during a trial. The first time a subject encountered a display-on trial and the display activated, they learned how to correct the position of the robot. Thereafter, they able to better avoid the display and the incorrect position. In some cases the first display-on trial was the first trial of that handrail color, and in other cases it was the second trial. In either case, the task time dropped significantly after the first activated display-on trial. However, there was no significant difference between display-on and display-off trial times which indicates that the display did not increase the task time – it was so intuitive that the subjects could correct for the errors quickly and continue on with the trial - precisely what it was designed to do. Therefore the display was able to significantly improve learning without increasing workload and/or task time.

Subject 2 did not execute any errors during the experiment. This is likewise due to the effects of display on learning. For each handrail color, Subject 2 was able to complete the first display-on trial without activating the display. This indicated to the subject that that their chosen arm and hand motion was within limits and would not trigger a warning. As the goal was to accurately align the hand on the handrail without breaching position and collision limits, this subject learned from the first trial that their method was successful and subsequently continued using that method for the duration of the trials.

The gender effects confirm the integrated test results in that no significant difference in task time was observed between male and female subjects. The number of errors was greatest for the excessive elbow height condition and occurred in both green and white trials, although the white trials were not designed specifically to elicit near-reach-limit motions. During white trials, subjects often perceived the handrail to be higher relative to their torso than it actually was and therefore raised their arm in anticipation of this height, resulting in several elbow-height warnings. Subjects completing green and yellow handrail trials could command the arm near a reach limit. When the simulation or robot is commanded beyond or near a reach limit, its internal processes tend to override the incoming command. This led subjects to believe that the arm was not following properly and indeed they experienced a difficult time commanding the arm near the operating limits. Since the green handrail was designed to be very near the reach limit, it is not surprising that this warning was most common. The yellow handrail task was designed to elicit self-collisions and indeed 22 such collisions occurred.

One of the intended benefits of the simulation was to incorporate its use in training protocols if in fact it proved to be useful in training operators via these experiments. Indeed, no significant difference in task time was found between novice and experienced users. Novice users did make a significantly larger number of blue-display errors that experienced subjects, however no difference was found for red-display errors. This could be due to the increased level of difficulty of the green handrail task in that the experience level better prepared subjects for the types of movements that might induce errors. It is expected that novice users would make more mistakes, however since their task times were not significantly larger in comparison, it demonstrates the utility of such an intuitive and minimal-workload display. Within one session, novice users were as aware of potential robot hazards, proper robot operating procedures, hazardous robot positions and methods to mitigate errors as experienced operators. This in effect, is operator training verification. Robosim can be used to prepare future Robonaut operators for general teleoperation tasks within a single session.

9 Conclusions and Contributions

Happy is he who gets to know the reasons for things.
Virgil (70-19 BCE) Roman poet

9.1 Conclusions and Contributions

The first contribution is the simple yet powerful classification of the EVA and robotic task space as a whole into three distinct elements. Gross position, fine position and grasping movements are the cornerstone motions to all EVA and robotic tasks. As opposed to evaluating peg-in-hole or target acquisition tasks specially designed for a particular robot testbed, it is suggested that researchers need to study the performance of these individually as well as in an integrated context so as to understand where the performance roadblocks arise, and where the need for situation awareness aids arises. The importance of the transitions between basis movements has been experimentally verified in a series of integrated trials.

A baseline amount of SA time (percentage of the total task time spent solely on obtaining and maintaining SA) was determined to exist through the completion of two different sets of integrated tasks using two different telerobots. The consistency of the result in both cases reveals an aspect of teleoperation performance not previously measured. A future area for study would be to discover the lower boundary of this pure SA time operators need to perform their tasks. It is not suspected that this time could be completely eliminated, however these experiments have shown that it can be reduced with the addition of displays or SA aids. An iterative process should be employed to develop and refine such SA aids and interfaces, identifying system issues and requirements before synthesizing and evaluating a display solution.

A powerful robotic research tool has been constructed and tested in the form of a graphical simulation. These experiments have demonstrated that Robonaut telerobotic performance can be similarly achieved using Robosim. The practicality of Robosim is enhanced in that it can be upgraded with enhanced capabilities as the robot itself continues to be upgraded. Likewise, internal robot hardware functions irrelevant to the human task performance and invisible to the user do not necessarily need to be modeled. Robosim can be used in place of the robot hardware to study the effects of different workstation components, different control algorithms, data stream management schemes, etc. The testbed nature of the simulation was verified by a testing, re-design and re-testing procedure. Results obtained in the first tests were confirmed in subsequent tests.

The final experiment also confirmed the simulation's use as a training tool by including 4 novice operators. As might be expected, the novice subjects made a greater number of errors during the most difficult task, however overall, the display increased their learning to the extent that there was no overall difference in task times between novice and experienced subjects. Again, this validates the ability for the simulation to be used for operator training. In summary, Robosim can be used in the future to develop Robonaut workstation situation awareness aids, as well as to develop an operator skill set.

The overall method employed here involved the study of teleoperator behavior to develop an understanding of the underlying performance characteristics of full-immersion teleoperators. Roadblocks to performance enhancements identified from these basis tasks yielded an initial display design for use during contextual task testing (integrated tasks). With the results from the initial design and the confirmation of Robosim and Robonaut performance similarities, the display was re-designed to target specific shortcomings of the first attempted solution. Robosim was then utilized for a re-test and results showed that a performance increase occurred without a corresponding increase in operator workload. Iterating on this integrated design process as many times as necessary will yield a design solution that can be applied with confidence to the robot hardware.

9.2 Future Work

The experiments conducted here limited the subject's control authority to 7 DOF during all tasks. A study of basis and integrated tasks could be performed with both arms and hands in the future, perhaps including the torso as well. However, given the number of close calls and errors encountered with only one arm operations, several design iterations using the above method should be done to ensure that some SA measures are in place to keep subject's aware of their total number of degrees of freedom in their environment throughout the tasks. It would also be desired to upgrade the simulation to contain contact force information, and as sensors are brought on-line on the robot hardware, these same data packets can be incorporated into the simulation. This would allow the study of grasping effects on performance using the simulation.

A second KC-135 experiment conducted with a greater numbers of subjects could reveal important roadblocks to providing sufficient SA to a full-immersion teleoperator in microgravity. Astronauts are not accustomed to their posture and body motion being tracked for robot commanding, therefore an appreciation for the effect of the lack of damping of body motions on command inputs is of particular interest. Astronauts also report keeping a sense of local vertical inside the spacecraft however if operating Robonaut through an HMD, the exterior orientation or the robot may not match the IVA astronauts standard and could lead to space motion sickness. A KC-135 experiment could also reveal the effects of the HMD vision on an IVA astronaut (the very effect that led to the illness of one of the Texas-Fly High students during the task trials).

Finally, increasing the length of task times and the complexity of EVA tasks tested to more closely resemble on-orbit operations could reveal interesting long term training, fatigue and high-stress effects. The more studies that can result in an understanding of the ultimate operating environment of the robot, the better able we will be to design the most appropriate telerobotic workstation for space applications.

APPENDICES

Appendix A Acronym List

CH	Cooper-Harper
CNS	Central Nervous System
DART	Dexterous Anthropomorphic Robotic Testbed
DOF	Degree of Freedom
DRL	Dexterous Robotics Laboratory
EMU	Extravehicular Mobility Unit
EVA	Extravehicular Activity
FITT	Full Immersion Telepresence Testbed
HMD	Head Mounted Display
HUD	Heads Up Display
IGOAL	Interactive Graphics Operations and Analysis Laboratory
IV	Intravehicular
IVA	Intravehicular Activity
JSC	Johnson Space Center
NASA	National Aeronautics and Space Administration
NDDS	National Television Standards Committee
NTSC	Network Data Delivery Service
ORU	Orbital Replacement Unit
POR	Point of Resolution

RTI	Real Time Innovations
SA	Situation Awareness
SGI	Silicon Graphics Inc.
SPDM	Special Purpose Dexterous Manipulator
SRMS	Shuttle Remote Manipulator System
SS	Sensory Substitution
SSRMS	Space Station Remote Manipulator System
SWAT	Subjective Workload Assessment Technique
TLX	Task Load Index
VEVI	Virtual Environment Vehicle Interface
VGA	Vide Graphics Adapter
VR	Virtual Reality

Appendix B Subject Consent Forms

B.1 NASA Internal Review Board Informed Consent

NASA/JSC HUMAN RESEARCH INFORMED CONSENT *

1. I, the undersigned, do voluntarily give my informed consent for my participation as a test subject in the following research study, test, investigation, or other evaluation procedure:

NAME OF INVESTIGATION Space Station Human Factors

FLIGHT TO WHICH ASSIGNED N/A

PRINCIPAL INVESTIGATOR Jennifer Rochlis

RESPONSIBLE NASA PROJECT SCIENTIST Jennifer Rochlis

I understand or acknowledge that :

(a) This procedure is part of an investigation approved by NASA.

(b) I am performing these duties as part of my employment with ____________ .

© This research study has been reviewed and approved by the JSC Institutional Review Board (IRB) which has also determined that the investigation involves minimal risk to the subject.
(minimal or reasonable)

(d) Definitions:

"Minimal risk" means that the probability and magnitude of harm or discomfort anticipated in the research are not greater in and of themselves than those ordinarily encountered in daily life or during the performance of routine physical or psychological examinations or tests.

"Reasonable risk" means that the probability and magnitude of harm or discomfort anticipated in the research are greater in and of themselves than those ordinarily encountered in daily life or during the performance of routine physical or psychological examinations or tests, but that the risks of harm or discomfort are considered to be acceptable when weighed against the anticipated benefits and the importance of the knowledge to be gained from the research.

(e) The research procedures were explained to me prior to the execution of this form. I was afforded an opportunity to ask questions, and all questions asked were answered to my satisfaction. A layman's description was provided to me. **

(f) I am medically qualified to participate in the investigation.

(g) I know that I can refuse to participate in the tests at any stage of their performance, and my refusal will be honored, except in those cases when, in the opinion of the responsible physician, termination of the tests could have detrimental consequences for my health and/or the health of the other subjects. I further understand that my withdrawal or refusal to participate in this investigation will not result in any penalty or loss of benefits to which I am otherwise entitled.

(h) In the event of physical injury resulting from this study and calling for immediate action or attention, NASA will provide or cause to be provided, the necessary treatment. I also understand that NASA will pay for any claims of injury, loss of life or property damage to the extent required by the Federal Employees Compensation Act or the Federal Tort Claims Act. My agreement to participate shall not be construed as a release of NASA or any third party from any future liability which may arise from, or in connection with, the above procedures.

(i) Except as provided for by Agency-approved routine uses under the Privacy Act, the confidentiality of any data obtained as a result of my participation as a research subject in this study shall be maintained so that no data may be linked with me as an individual. I understand, however, that if a "life-threatening" abnormality is detected, the investigator will notify me and the JSC Flight Medicine Clinic. Such information may be used to determine the need for care or medical follow-up, which, in certain circumstances, could affect my professional (flight) status.

Signature:	Signature:
____________________	____________________
Test Subject Date	Witness Date

2. I, the undersigned, the Principal Investigator of the investigation designated above, certify that:

(a) I have thoroughly and accurately described the research investigation and procedures to the test subject and have provided him/her with a layman's description of the same.

(b) The test setup involves ________________ (minimal or reasonable) risk to the test subject. All equipment to be used has been inspected and certified for safe and proper operation.

© The test subject is medically qualified to participate.

(d) Except as provided for by Agency-approved routine uses under the Privacy Act, the confidentiality of any data obtained as a result of the test subject's participation in this study shall be maintained so that no data may be linked to him/her as an individual.

(e) The test protocol has not been changed from that originally approved by the JSC IRB.

Signature:	Signature:
____________________	____________________

Principal Investigator Date NASA Project Scientist Date

Notes:

* This form is valid for the period including preflight, in-flight, and postflight data collection sessions for the mission. Before the first baseline data collection, the Principal Investigator will repeat the briefing concerning risks involved in the investigation. A signed, dated copy of this form with attachments must be forwarded to Chairperson,

Johnson Space Center Institutional Review Board, Attn: Dr. Lawrence Dietlein, Mail Code SA, Lyndon B. Johnson Space Center, Houston, Texas 77058.

** A detailed description of the investigation will be attached to this consent form. The Principal Investigator is responsible for formulating this document, which should be in layman's terms such that the subject clearly understands what procedures will be required of him/her and the risks associated therewith.

The detailed description of the research must, at a minimum, include the following:

(1) An explanation of the purposes of the research and the expected duration of the subject's participation, a description of the procedures to be followed, and identification of any procedures which are experimental;

(2) A description of any reasonably foreseeable risks or discomforts to the subject, including, but not limited to, possible adverse reactions of all medications to be administered and any risks/hazards resulting from exposure to ionizing radiation;

(3) A description of any benefits to the subject or to others which may reasonably be expected from the research;

(4) A disclosure of appropriate alternative procedures or courses of treatment, if any, that might be advantageous to the subject;

(5) A statement describing the extent, if any, to which confidentiality of records identifying the subject will be maintained;

(6) Clarification of all forms of behavior, if any, interdicted by the research protocol (e.g., exercise, diet, medications, etc.); and

(7) An explanation of whom to contact for answers to pertinent questions about the research and research subjects' rights, and whom to contact in the event of a research-related injury to the subject.

When appropriate, the following information shall also be provided in the detailed description:

(8) A statement that the particular treatment or procedure may involve risks to the subject (or to the embryo or fetus, if the subject is or may become pregnant) which are currently unforeseeable;

(9) Anticipated circumstances under which the subject's participation may be terminated by the investigator without regard to the subject's consent;

(10) Any additional costs to the subject that may result from participation in the research;

(11) The consequences of a subject's decision to withdraw from the research and procedures for orderly termination of participation by the subject;

(12) A statement that significant new findings developed during the course of the research which may relate to the subject's willingness to continue participation will be provided to

the subject; and

(13) The approximate number of subjects involved in the study.

B.2 Dexterous Robotics Laboratory Informed Consent Form

DEXTEROUS ROBOTICS LABORATORY

SPACE STATION HUMAN FACTORS: DESIGNING AN INTEGRATED TELEROBOTIC WORKSTATION
SUBJECT
CONSENT FORM

I have been asked to participate in a study designed to investigate human performance of telerobotic tasks. I understand that participation is voluntary and that I may withdraw consent and discontinue participation at any time for any reason.

I understand that this experiment will be conducted in the Dexterous Robotics Laboratory at JSC. I will be seated in a chair and will don a Helmet Mounted Display and for some tasks, sensor-instrumented gloves. I will be asked to perform grasping, large motion, alignment and EVA-like tasks in three interfaces - manually, telerobotically and simulated. In the latter two cases I will wear an HMD and instrumented gloves and my motions will be tracked to either a robot or a graphical model of the robot. The experiment will be conducted in 6 (two for each interface) sessions of one to one-and-a-half hours each to be scheduled at my own convenience. Prior to the first session for a give interface, a fifteen-minute practice session will be conducted so that I may familiarize myself with the equipment. In addition, the experimenter will summarize the tasks I will perform. After each fifteen minutes of total task time I will be given a resting period of three to five minutes during which I may remove any equipment I so choose. There have been no known incidences of adverse reactions or hazards associated with HMD of instrumented glove use.

Upon completion of each interface, I will be given a questionnaire to be filled out on a computer designed to investigate my experiences with the session. I understand that no personal information will be attached to my responses. I also understand that all data from my session will be coded with a subject number - at no time will my identity be linked with the results unless I give consent to the principal investigator.

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the JSC Medical Clinic, including first aid emergency treatment and follow-up care as needed. As the subjects are NASA or NASA contractor employees, NASA is responsible for compensation for injury, death or property damage to the extent required by the Federal Employees Compensation Act or the Federal Tort Claims Act.

I understand I will receive no compensation for participating in this experiment and that I may receive answers to any questions related to this experiment by contacting the Principal Investigator at (281) 483-1718.

I understand that I may also contact the JSC Institutional Review Board if I feel I have been treated unfairly as a subject.

I have been informed as to the nature and purpose of this experiment and the risks involved, and agree to participate in the experiment. I understand that participation in this experiment is voluntary, and I am free to withdraw my consent and to discontinue participation in the study at any time without prejudice.

Subject Name (Print)____

Subject signature____

Date ____________

Experimenter ____

Date ____________

Appendix C MATLAB Scripts

The following appendix contains the MATLAB programs written for data reduction purposes. The data packet recorded by the computer is shown in Table C.1 below in raw form. Each frame (data recorded at 10 Hz) is stamped with the date and time (hh:mm:ss:msec). The data recorded is one of three values, a joint angle, POR force or POR moment. Joint angles are labeled by the name of the joint in the Enigma model (i.e. Shoulder_Pitch_R – right arm shoulder pitch angle, or index1_yaw_R – right hand index finger joint 1 yaw angle). The forces and moments are all measured with respect to the POR and are labeled zero through five for each of the three axes, Fx, Fy, Fz, Mx, My, Mz respectively.

Table C.1 Raw Integrated Task Data

Frame 6/4/2001 13:24:47:406
Shoulder_Roll_R -18.627063 Shoulder_Pitch_R -58.616604 Elbow_Roll_R 78.370746 Elbow_Pitch_R -112.431126 Fore_Arm_Roll_R -45.940446 Wrist_pitch_R 17.637953 Wrist_yaw_R 9.102763 RightForce(0) -0.651255 RightForce(1) 0.478301 RightForce(2) 1.392753 RightMoment(3) 1.037124 RightMoment(4) 2.718940 RightMoment(5) -4.248929 tyoke_yaw_R -38.846784 thumb1_yaw_R -8.135193 thumb2_yaw_R 12.645249 index_yaw_R 2.376795 index1_yaw_R 1.677848 index2_yaw_R 10.248409 index3_yaw_R 1.302363 middle_yaw_R 1.302363 mid1_yaw_R 9.360376 mid2_yaw_R 6.226236 mid3_yaw_R 0.009340 ring_yoke_yaw_R 0.004670 ring1_yaw_R 4.699803 ring2_yaw_R 4.699803 ring3_yaw_R 4.699803 pink_yoke_yaw_R 0.009340 pink1_yaw_R 7.763087 pink2_yaw_R 7.763087 pink3_yaw_R 7.763087

In order to extract and plot the force data, two scripts were written. The first script titled "dataimport.m" read in the raw data file, selected out the force and moment strings and created and excel file with a matrix of [Fx Fy Fz Mx My Mz], a sample of which is shown in Table C.2.

Table C.2 Sample of matrix data created by dataimport.m

Fx	Fy	Fz	Mx	My	Mz
-0.65126	0.478301	1.392753	1.037124	2.71894	-4.24893
-0.91748	0.620826	1.334794	1.126783	2.994867	-4.38228
-0.81216	1.173518	1.208897	1.440279	3.265311	-6.53807
-0.48279	0.95144	1.20448	1.587752	2.228215	-5.74117
-0.80104	0.41905	1.371543	1.057285	2.633015	-4.43631

The second script titled "FMplot.m" took the excel file created and plotted the data in a series of 6 subplots of magnitude versus frame. This graph (Figure B.1) shows the force and moment traces of the trials from beginning to end (a handrail task in this example).

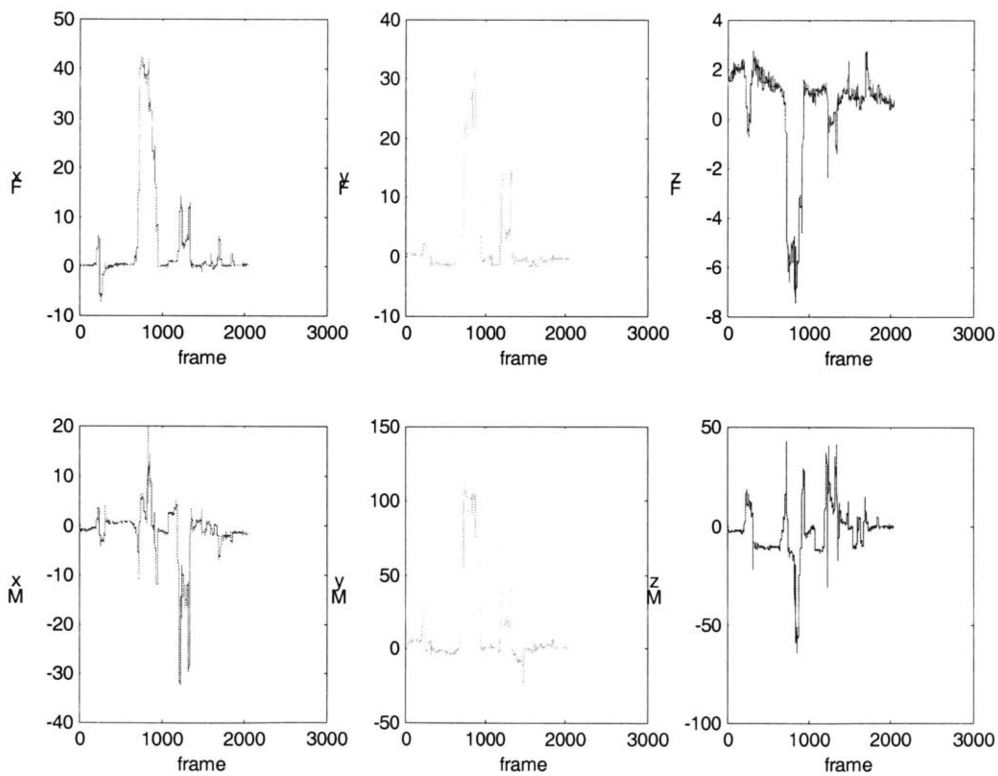


Figure C.1 Sample force and moment trace from drill task

dataimport.m

```
fid = fopen('F:\Thesis\data\RoboData\Integrated\Subject5\temp5int_6.dat','w');
[data] =
textread('F:\Thesis\data\RoboData\Integrated\Subject5\int5_6.JEN','%s');
i = 1;
while i < length(data)
   if strncmp(data(i),'RightForce(0)',13)
    i = i + 1;
for j = 1:6
fprintf(fid,'%s \n',data{i});
i = i + 2;
      end
   end
   i = i + 1;
end
fclose(fid);
fid = fopen('F:\Thesis\data\RoboData\Integrated\Subject5\temp5int_6.dat','r');
[forcedata] =
textread('F:\Thesis\data\RoboData\Integrated\Subject5\temp5int_6.dat','%f');
k = 1;
while k <= length(forcedata)
   for m = 1:length(forcedata)/6
    Fx(m) = forcedata(k);
    Fy(m) = forcedata(k+1);
    Fz(m) = forcedata(k+2);
    Mx(m) = forcedata(k+3);
    My(m) = forcedata(k+4);
    Mz(m) = forcedata(k+5);
    k = k + 6;
end
end
FMmatrix = [Fx' Fy' Fz' Mx' My' Mz'];
fid2 = fopen('F:\Thesis\data\RoboData\Integrated\Subject5\FMint5_6.dat','w');
q = size(FMmatrix);
numrow = q(1,1);
numcol = q(1,2);
for n = 1:numrow
   for p = 1:numcol
      fprintf(fid2,'%f \t', FMmatrix(n,p));
    end
    fprintf(fid2,'\n');
end
```

```
fclose(fid2);
```

FMPlot.m

```
[Fx, Fy, Fz, Mx, My, Mz] =
textread('F:\Thesis\data\RoboData\Integrated\Subject6\FMint6_12.dat','%f %f
%f %f %f %f');
q = length(Fx);
t = (0:1:q-1);

subplot(2,3,1);
plot (t,Fx,'r');
Xlabel('frame');
Ylabel('Fx');

subplot(2,3,2);
plot (t,Fy,'g');
Xlabel('frame');
Ylabel('Fy');

subplot(2,3,3);
plot (t,Fz,'b');
Xlabel('frame');
Ylabel('Fz');

subplot(2,3,4);
plot (t,Mx,'r');
Xlabel('frame');
Ylabel('Mx');

subplot(2,3,5);
plot (t,My,'g');
Xlabel('frame');
Ylabel('My');

subplot(2,3,6);
plot (t,Mz,'b');
Xlabel('frame');
Ylabel('Mz');

minFx = min(Fx);
maxFx = max(Fx);
```

```
minFy = min(Fy);
maxFy = max(Fy);
minFz = min(Fz);
maxFz = max(Fz);

minMx = min(Mx);
maxMx = max(Mx);

minMy = min(My);
maxMy = max(My);

minMz = min(Mz);
maxMz = max(Mz);

MIN = [minFx; minFy; minFz; minMx; minMy; minMz]
MAX = [maxFx; maxFy; maxFz; maxMx; maxMy; maxMz]
```

Appendix D RoboRecorder

One of the tools used in the data analysis process was the RoboRecorder developed by Mike Goza at JSC. This program allowed for the playback of the recorded trial data files. The motions commanded by the subject during the trials are displayed in real time using the Robosim Enigma animation software. Figure D.1 shows the dialog boxes for the RoboRecorder.

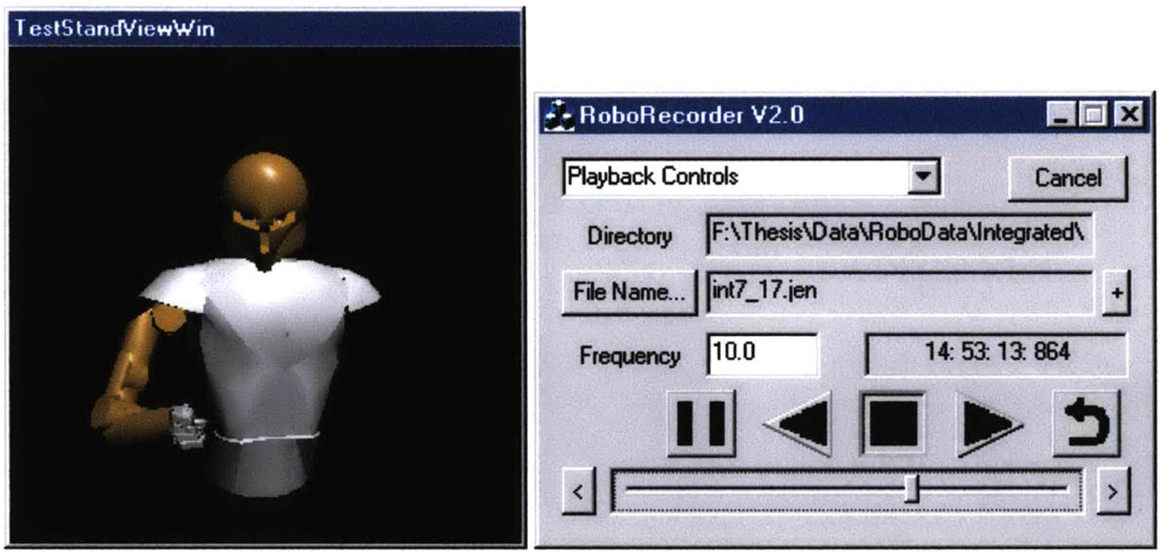


Figure D.1 RoboRecorder

The graphics window is displaying the position of all Robonaut joints at the recorded time of 14:53:13:864 as shown in the RoboRecorder graphical used interface (GUI). At the moment shown here, the subject is grasping the drill during the integrated drill task. The GUI includes the following controls and displays:

Playback Controls – Shown here in playback mode but can also be in Record Data mode where data that is streaming from Robonaut is recorded.

Directory - In the properties menu you can select the default directory for the files to be played back from, or recorded to

File Name - Shows the current file being played back/recorded

Frequency -

Displays the frequency of the data stream

Windows -

The time stamp is displayed next to the frequency

Controls –

Controls include pause, rewind, stop, play, loop and a slider for the playback mode. In record mode, controls are included for record, stop and pause

Appendix E Robosim Structure and Configuration Files

E.1 Configuration File Description

The following file, called the configuration file, acts as an interface to the simulation code. This file contains a number of fixed variables (such as the DH parameters) as well as a number of parameters that the experimenter may want to adjust. The first part of the file lists the file paths where the geometrical models are located. The second section, ROBONAUT CONFIGURATION DATA, contains the information that is most accessed buy the user. Here, the structure file that contains the Robonaut model is listed, along with which windows in that structure file the used wishes to have drawn on the right or left computer (denoted RIGHT_WINDOW and LEFT_WINDOW respectively). The frame rate, NDDS channels and other particulars are also available here. The third section, PUBLISH, contains a list of the Robonaut model segments that the simulation will publish data packets on. Data packet names, update rate data for that packet and most importantly, and ON/OFF toggle are listed here. Notice that in this case, the left arm and hand are turned off (since we are only doing right handed operations), as well as the right hand (since the hand is in a fixed position throughout the trial). Under the SUBSCRIBE section is listed the Robonaut model segments that the simulation is listening for data about. Again, the left hand and arm and right hand are turned off. The remainder of the file contains the particular DH parameters and limits for each of the joints, listed with their structure file nomenclature.

E.2 Laboratory Experiment B Configuration File

The first full file listed is for laboratory experiment B. The files used for the KC-135 and integrated trials are identical with the exception of the structure file name. A different structure file was used for the first two experiments that placed the hand in a pointing position and contained the virtual task panels. Experiment B used a structure file with the hand in a cupped position and the handrails. During the integrated experiments, the NDDS domain was listed as the Robonaut domain of zero in order to publish and listen to Robonaut's communication channel. Experiment B ran on domain five to be isolated from other concurrent robot experiments being conducted in the laboratory.

```
#   IGL ENVIRONMENT PATHS
@VMOD ../MODELS/ARMJOINTS
@VMOD ../MODELS/BODY
@VMOD ../MODELS/HANDWRIST
@VMOD ../MODELS/HEAD
@VMOD ../MODELS/OTHER
@VMOD ../MODELS/STAND
@VMOD ../MODELS/TAILJOINTS
#
@AMOD ../MODELS/ARMJOINTS
@AMOD ../MODELS/BODY
@AMOD ../MODELS/HANDWRIST
@AMOD ../MODELS/HEAD
@AMOD ../MODELS/OTHER
@AMOD ../MODELS/STAND
@AMOD ../MODELS/TAILJOINTS
@STR ../STRUCTS
@FONTDATA ../FONT_DATA
#
#   ROBONAUT CONFIGURATION DATA
#
@STRUCT_FILE     robonautmikeNiska.str
@LEFT_WINDOW     TestStandViewWin
#@LEFT_WINDOW    LeftWindow
#@RIGHT_WINDOW   TestStandViewWin
@RIGHT_WINDOW    RightWindow
@FRAME_RATE_HZ       20
@NDDS_DOMAIN  5
#@BUTTON_NODE    Fitts
#@SQUARE_NODE    SquareTrace
#@TARGET_NODE Target
#
#PUBLISH
#                    PACKET NAME  PERSISTENCE  STRENGTH     SEND_RATE_HZ  ON/OFF
@PUBLISH_RIGHT_HAND  DEFAULT      15.0         1.0          20.0          OFF
@PUBLISH_RIGHT_ARM   DEFAULT      15.0         1.0          20.0          ON
@PUBLISH_LEFT_HAND   DEFAULT      15.0         1.0          20.0          OFF
@PUBLISH_LEFT_ARM    DEFAULT      15.0         1.0          20.0          OFF
@PUBLISH_HEAD        DEFAULT      15.0         1.0          20.0          ON
@PUBLISH_TAIL        DEFAULT      15.0         1.0          20.0          ON
#
```

```
#
#SUBSCRIBE
#                          PACKET NAME  MINSEP       DEADLINE      ON/OFF
@SUBSCRIBE_LEFT_HAND       DEFAULT      0.0          1000.0        OFF
@SUBSCRIBE_LEFT_ARM        DEFAULT      0.0          1000.0        OFF
@SUBSCRIBE_RIGHT_HAND      DEFAULT      0.0          1000.0        OFF
@SUBSCRIBE_RIGHT_ARM       DEFAULT      0.0          1000.0        ON
@SUBSCRIBE_HEAD            DEFAULT      0.0          1000.0        ON
@SUBSCRIBE_TAIL            DEFAULT      0.0          1000.0        ON
#
#  RIGHT ARM DATA
#
#  RIGHT ARM BASE TRANSFORM      XYZ                 RPY
#
@RIGHT_ARM_BASE                 0.0 0.0 0.0         -90.0 0.0 90.0
@RIGHT_ARM_TOOL                 0.0 0.0 0.0         0.0 0.0 0.0
@RIGHT_ARM_MODE                 CARTESIAN
#
#RIGHT SHOULDER DATA
#             NODE               DH_A  DH_ALPHA  DH_D   DH_OFF  RATE    MIN    MAX
@RIGHT_ARM_0  Shoulder_Roll_R    -2.0  -90.0  12.25    0.0    13.0  -45.0  100.0
@RIGHT_ARM_1  Shoulder_Pitch_R    2.0   90.0   0.00    0.0    13.0 -110.0  -30.0
@RIGHT_ARM_2  Elbow_Roll_R       -2.0  -90.0  12.75    0.0    13.0    0.0  180.0
@RIGHT_ARM_3  Elbow_Pitch_R       2.0   90.0   0.00    0.0    13.0 -135.0  -30.0
@RIGHT_ARM_4  Fore_Arm_Roll_R     0.0  -90.0  14.50    0.0    40.0 -180.0   50.0
@RIGHT_ARM_5  Wrist_pitch_R       0.0   90.0   0.00  -90.0   100.0  -40.0   40.0
@RIGHT_ARM_6  Wrist_yaw_R         1.5    0.0  -0.50    0.0   100.0  -20.0   20.0
#
#  RIGHT HAND DATA
#
@RIGHT_HAND_THUMB_0 tyoke_yaw_R     0.0    0.0    0.0   0.0    15.0  -60.0    5.0
@RIGHT_HAND_THUMB_1 thumb1_yaw_R   0.25   90.0    0.0   8.9    15.0  -30.0   85.0
@RIGHT_HAND_THUMB_2 thumb2_yaw_R  1.844    0.0    0.0 -10.0    15.0   10.0   85.0
@RIGHT_HAND_THUMB_MODE     JOINT
#
@RIGHT_HAND_INDEX_0 index_yaw_R     0.0    0.0    0.0   0.0    15.0  -20.0   20.0
@RIGHT_HAND_INDEX_1 index1_yaw_R  0.317   90.0    0.0  -5.9    15.0  -10.0   85.0
@RIGHT_HAND_INDEX_2 index2_yaw_R    1.8    0.0    0.0   0.0    15.0    0.0   85.0
@RIGHT_HAND_INDEX_3 index3_yaw_R   1.05    0.0    0.0   5.9    15.0    0.0   85.0
@RIGHT_HAND_INDEX_MODE     JOINT
#
@RIGHT_HAND_MIDDLE_0 middle_yaw_R   0.0    0.0    0.0   0.0    15.0  -20.0   20.0
@RIGHT_HAND_MIDDLE_1 mid1_yaw_R   0.317   90.0    0.0  -5.9    15.0  -10.0   85.0
@RIGHT_HAND_MIDDLE_2 mid2_yaw_R     1.8    0.0    0.0   0.0    15.0    0.0   85.0
@RIGHT_HAND_MIDDLE_3 mid3_yaw_R    1.05    0.0    0.0   5.9    15.0    0.0   85.0
@RIGHT_HAND_MIDDLE_MODE    JOINT
#
@RIGHT_HAND_RING_0  ring_yoke_yaw_R 0.0    0.0    0.0   0.0    15.0   0.0    15.0
@RIGHT_HAND_RING_1  ring1_yaw_R   0.405 -20.33 -4.094 -86.3    15.0   0.0    85.0
@RIGHT_HAND_RING_2  ring2_yaw_R   1.602    0.0    0.0  0.71    15.0   0.0    85.0
@RIGHT_HAND_RING_3  ring3_yaw_R    1.05    0.0    0.0  5.95    15.0   0.0    85.0
@RIGHT_HAND_RING_MODE      JOINT
#
@RIGHT_HAND_PINKY_0 pink_yoke_yaw_R 0.0    0.0    0.0   0.0    15.0   0.0    30.0
@RIGHT_HAND_PINKY_1 pink1_yaw_R   0.531 -12.89 -7.884 -82.5    15.0   0.0    85.0
@RIGHT_HAND_PINKY_2 pink2_yaw_R   1.602    0.0    0.0  0.71    15.0   0.0    85.0
@RIGHT_HAND_PINKY_3 pink3_yaw_R    1.05    0.0    0.0  5.95    15.0   0.0    85.0
@RIGHT_HAND_PINKY_MODE     JOINT
#
#LEFT ARM DATA
#
#             PACKET NAME  PERSISTANCE  STRENGTH      SEND_RATE_HZ  ON/OFF
#LEFT ARM BASE TRANSFORM   XYZ          RPY
```

```
#
@LEFT_ARM_BASE      0.0 0.0 0.0         90.0 0.0 -90.0
@LEFT_ARM_TOOL      0.0 0.0 0.0         0.0 0.0 0.0
@LEFT_ARM_MODE      CARTESIAN
#
#  LEFT SHOULDER DATA
#
@LEFT_ARM_0   Shoulder_Roll_L  -2.0  -90.0  12.25   0.0  13.0  -100.0   45.0
@LEFT_ARM_1   Shoulder_Pitch_L  2.0   90.0   0.00   0.0  13.0  -110.0  -30.0
@LEFT_ARM_2   Elbow_Roll_L     -2.0  -90.0  12.75   0.0  13.0  -180.0    0.0
@LEFT_ARM_3   Elbow_Pitch_L     2.0   90.0   0.00   0.0  13.0  -135.0  -30.0
@LEFT_ARM_4   Fore_Arm_Roll_L   0.0  -90.0  14.50   0.0  40.0   -50.0  180.0
@LEFT_ARM_5   Wrist_pitch_L     0.0   90.0   0.00 -90.0 100.0   -40.0   40.0
@LEFT_ARM_6   Wrist_yaw_L       1.5    0.0  -0.50   0.0 100.0   -20.0   20.0
#
#  LEFT HAND DATA
#
@LEFT_HAND_THUMB_0  tyoke_yaw_L   0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_THUMB_1  thumb1_yaw_L  0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_THUMB_2  thumb2_yaw_L  0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_THUMB_MODE            JOINT
#
@LEFT_HAND_INDEX_0  index_yaw_L   0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_INDEX_1  index1_yaw_L  0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_INDEX_2  index2_yaw_L  0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_INDEX_3  index3_yaw_L  0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_INDEX_MODE            JOINT
#
@LEFT_HAND_MIDDLE_0 middle_yaw_L  0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_MIDDLE_1 mid1_yaw_L    0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_MIDDLE_2 mid2_yaw_L    0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_MIDDLE_3 mid3_yaw_L    0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_MIDDLE_MODE           JOINT
#
@LEFT_HAND_RING_0 ring_yoke_yaw_L 0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_RING_1   ring1_yaw_L   0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_RING_2   ring2_yaw_L   0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_RING_3   ring3_yaw_L   0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_RING_MODE             JOINT
#
@LEFT_HAND_PINKY_0 pink_yoke_yaw_L 0.0 0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_PINKY_1  pink1_yaw_L   0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_PINKY_2  pink2_yaw_L   0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_PINKY_3  pink3_yaw_L   0.0  0.0   0.0   0.0   15.0  -180.0 180.0
@LEFT_HAND_PINKY_MODE            JOINT
#
#
#  HEAD JOINTS
#
@HEAD_BASE                        0.0    0.0  -4.75  180.0      0.0     0.0
@HEAD_TOOL                        0.0    0.0   0.0    0.0       0.0     0.0
#@HEAD_0      Neck_Yaw     2.0   -90.0   5.71   0.0   20.0     -75.0   75.0
#@HEAD_1      Neck_Pitch   0.0     0.0   0.0   30.0   20.0     -50.0   60.0
@HEAD_0       Neck_Yaw     2.0   -90.0   5.71   0.0  200.0    -180.0  180.0
@HEAD_1       Neck_Pitch   0.0     0.0   0.0   30.0  200.0    -180.0  180.0
@HEAD_MODE                       CARTESIAN
#
#
#  TAIL JOINTS
#
@TAIL_BASE                       0.0 0.0 0.0            0.0 0.0 0.0
@TAIL_TOOL                       0.0 0.0 0.0            180.0 0.0 0.0
#@TAIL_0      Body_Roll    -3.0  -90.0 -21.94  0.0   14.0    -90.0     90.0
```

```
#@TAIL_1      Hip_Pitch     3.0   -90.0    0.0   0.0    9.0   -120.0    -60.0
#@TAIL_2      Hip_Roll     0.0     0.0  -12.0   0.0    9.0    -30.0     30.0
#
@TAIL_0       Hip_Roll     -3.0   -90.0   12.0   0.0    9.0    -30.0     30.0
@TAIL_1       Hip_Pitch     3.0    90.0    0.0   0.0    9.0   -120.0    -60.0
@TAIL_2       Body_Roll     0.0     0.0  21.94   0.0   14.0    -90.0     90.0
#@TAIL_0      Hip_Roll     -3.0   -90.0   12.0   0.0   90.0   -180.0    180.0
#@TAIL_1      Hip_Pitch     3.0    90.0    0.0   0.0   90.0   -180.0    180.0
#@TAIL_2      Body_Roll     0.0     0.0  21.94   0.0  140.0   -180.0    180.0
@@TAIL_MODE                 CARTESIAN
#
#
#  POLHEMUS DATA  (TEMPORARY)
#
@SUBSCRIBE_POLHEMUS        PolhemusCommand          0.0          1000.0
```

E.3 Robosim Structure File

The following is a sample of an enigma structure file used in these experiments. Parameters listed include the system node name, model node name, position and orientation, and environment variables.

```
Shoulder_Roll_R
          SYSTEM
           0.000000 6.482000 0.000000
           0.000000 0.000000 -90.000000
           Spine_New
           @order RPY
           @userdata Type Joint
           @userdata Base robody
           @userdata JointAxis Roll
           segment1_R
           MODEL
            segment1_enigma_trans
            0.000000 0.000000 0.000000
            90.000000 0.000000 -90.000000
            Shoulder_Roll_R
            @highres segment1.bin OFF
            @userdata Type Link
            @userdata Base robody
            Shoulder_Pitch_R
            SYSTEM
             -5.937500 0.000000 -2.000000
             -180.000000 -90.000000 90.000000
             segment1_R
             @order RPY
             @userdata Type Joint
             @userdata JointAxis Pitch
             @userdata Base robody
             @userdata ReverseSense true
             segment2_R
             MODEL
```

Appendix F Pilot Study Task

Table F.1 shows the data collected by NASA during underwater EVA astronaut training for a tool exchange collected in 1990 along with the DART/FITT version with the basis tasks noted in the order they are performed, as well as the average task time found during the pilot experiment (if applicable). This table lists pilot study task B, the tool exchange. The notation for the basis tasks is as follows, G = gross position, F = fine position, g = grasping. Note that series of basis tasks for each element is shown. Based on pilot experiments, a retraction and preparation step was observed before and after most movements. The preparation was often done mentally and visually, that is, without moving the robot body, the operator would scan with the head if at all. The retraction was always a gross position movement to return the arm to presumably a "neutral position" before rotation the body, or beginning the next task. The preparation step since it requires no motion of the body is therefore not noted in the chart, however the retraction is included as (G) at the end of some elements.

Table F.1 Tool Exchange with Times and Subtasks

Task Element	**NASA Avg. Time**	**Avg. Pilot Exp. Time**	**Basis Tasks**
Translate to toolbox	0:01:00	N/A	
turn body/base			G
Open toolbox door	0:01:02	0:01:20	
reach arm toward door handle			G
position hand over handle			F
grasp handle			g
open door			G
release grasp			g
retract arm			G

bring arm to second door			G
position over handle			F
grasp second handle			g
open door			G
release grasp			g
retract arm			G
Tether to tool	0:01:11	N/A	
reach arm toward tether			G
position hand over tether			F
grasp tether			g
actuate tether lock			g
bring tether to tool			G
position tether over tool			F
tether to tool			F
release grasp			g
retract hand			G
Open tool latch		0:00:27	
position fingers			g
bring hand to latch			G
actuate latch			F
retract hand			G
Release tool from toolbox		0:00:59	
position fingers			g
reach hard to tool			G
position hand over tool			F
grasp tool			g
retract hand			G
Translate to stanchion		0:00:32	
Turn body/base			G
Attach tool to stanchion		0:00:40	
Reach tool to stanchion			G

position over stow location stow tool retract hand			F F G
Release tether position fingers bring hand to tether position hand over tether grasp tether actuate tether lock retract tether from tool retract arm		N/A	 g G F g g F G
Tether to tool 2 reach hand toward tether position hand over tether grasp tether actuate tether lock bring tether to tool position tether over tool tether to tool release grasp retract hand		N/A	 G F g g G F F g G
Release tool 2 from stanchion reach hand towards tool position hand over tool grasp tool retract tool retract arm		0:00:48	 G F g F G
Translate to toolbox Turn body/base		0:00:32	 G
Attach tool 2 to toolbox reach arm to toolbox		0:00:49	 G

position hand over stow slot stow tool release grasp retract arm			F F g G
Close tool latch position fingers reach arm to latch position hand over latch actuate latch retract arm		0:00:23	 g G F F G
Release tether position fingers bring hand to tether position hand over tether grasp tether actuate tether lock retract tether from tool retract arm	0:00:21	N/A	 g G F g g F G
Close toolbox reach hand toward door handle position hand over handle grasp handle close door release grasp retract arm bring arm to second door position over handle grasp second handle close door release grasp retract arm	0:02:07	N/A	 G F g G g G G F g G g G

Appendix G Pilot Study Data

Table G.1 shows the data collected during the DART/FITT pilot study. Data is listed by subject, trial day and task (A – ORU change-out or B - Tool Exchange). Total time lists the total task time in seconds, while the SA time lists the SA time in seconds. The SA time was time that the subjects spent only gaining situation awareness, and not actively doing a task.

Table G.1 Pilot Study Data

SUBJECT	DAY	RUN	TASK	TOTAL TIME	SA TIME
1	1	1	A	1259	125
1	1	2	B	1091	56
1	1	3	A	1241	486
1	1	4	B	Wrist Failure	N/A
2	1	1	A	1452	169
2	1	2	B	1076	129
2	1	3	A	1341	179
2	1	4	B	Arm Failure	N/A
3	1	1	A	631	26
3	1	2	B	601	24
3	1	3	A	540	13
3	1	4	B	531	76
4	1	1	A	1071	133
4	1	2	B	1150	24
4	1	3	A	737	86
4	1	4	B	848	34
1	2	1	B	841	12
1	2	2	A	847	183
1	2	3	B	663	2
1	2	4	A	928	68
2	2	1	B	796	107
2	2	2	A	879	272
2	2	3	B	682	62
2	2	4	A	699	111
3	2	1	B	389	22
3	2	2	A	568	62
3	2	3	B	640	140
3	2	4	A	620	78
4	2	1	B	766	51
4	2	2	A	572	35
4	2	3	B	432	66
4	2	4	A	405	0

Appendix H Pilot Study Subjective Responses

The following sections contain the subjective questionnaire responses for the pilot DART/FITT study. Note that responses that are left blank are due to blank responses left by the subject on the questionnaire.

H.1 Section 1 Fatigue Questions

1) Number of hours of DART Experience

Subject	Response
1	30-40 hours
2	60 hours
3	12 hours
4	5-10 hours

2) On the first day of testing, did you experience and fatigue?
If so, where, and at what point during the test did this occur?

Subject	Response
1	Eye fatigue, half way through
2	Half way through
3	Back and neck, towards the end of testing
4	Mental, hands and shoulders

3) On the first day of testing, did you experience and fatigue?
If so, where, and at what point during the test did this occur?

Subject	Response
1	Half way through, tired of concentrating on teleoperation task
2	5^{th} experiment
3	Back and neck, towards the end of testing
4	Mental, hands and shoulders

4) What methods did you use to combat fatigue during the experiment?

Subject	Response
1	Rested between runs
2	Resting eyes during break
3	Resting between tests and pausing during experiments. Also relaxing one arm when not being used
4	Frequent breaks for shoulders and mental

5) Do you think any aspects of the fatiguing effects would be better or worse in microgravity?

Subject	Response
1	Eye fatigue would be unaffected. Overall fatigue would be increased as operator adapts to micro-g AND teleoperation interface simultaneously
2	Not necessarily
3	Better, less stress to support helmet
4	Only on the shoulders

6) Given EVAs can last up to 8 hours (almost 5x longer than these trials), what ways of reducing teleoperator fatigue can you suggest?

Subject	Response
1	Better task planning and simulation beforehand. Minimize delays in system and add auxiliary teleoperator views
2	Larger field of view helmet and associated camera system
3	Lighter/better balanced helmet
4	Improved grasping primitives, frequent breaks

H.2 Section 2 Specific Task Evaluation

1) Rate the overall difficulty of the ORU task, 1 being very easy, 5 being very difficult:

Response	Subjects responding
1	1
2	3
3	2,4
4	
5	

2) Please elaborate on the level of difficulty:

Response	Subjects responding
The entire task was easy	1
A few parts of the task were difficult, but most of the parts were easy	2,3, 4
Half of the task was easy, half difficult	
Most of the task was difficult, only a few parts were easy	
The entire task was difficult	

3) Which sections of the task, if any, did you find difficult, and why?

Subject	Response
1	None were difficult
2	Putting the drill into place – velcro kept coming loose – base motion too limited
3	Most difficult part of the task was replacing the drill – I couldn't reach the velcro
4	The drill location was at the edge of the workspace. Grabbing it was a hit

	or miss experience. Touching the bare bolts was also tough for the same reasons

4) Which sections, if any, did you find easy, and why?

Subject	Response
1	Everything was easy because no dexterous hand motion was necessary to complete any section
2	Door sliding and pin pulling
3	Opening and sliding doors, grasping the drill. Opening the doors doesn't require fine movements, just about any motion will open the door. Grasping the drill was easy because it is big and plenty of room for misalignment
4	Pin removal, door opening, touching the target

5) Did you find that the more times you did the task that it's level of difficulty:

Response	Subject responding
Increased	
Remained the same	3,4
Decreased	1, 2

6) Please explain the above response:

Subject	Response
1	There was some initial learning in the first run with less and less learning in subsequent repetitions. The learning curve was steep at first but leveled off quickly, but the learning was valuable
2	I became smarter. I used base motion instead of arm motion for door sliding
3	The tasks were relatively easy and repeatable. With more practice these tasks would probably get easier
4	So much of the difficulty came from the drill. It felt as though luck played a major role in the ease of the experiment

7) Rate the difficulty of the tool exchange task, 1 being very easy, 5 being very difficult:

Response	Subject responding
1	
2	
3	
4	1,2,3
5	4

8) Please elaborate on the level of difficulty:

Response	Subject responding
The entire task was easy	
A few parts of the task were difficult, but most of the parts were easy	

Half of the task was easy, half difficult	1
Most of the task was difficult, only a few parts were easy	2,3,4
The entire task was difficult	

9) Which sections of the task, if any, did you find difficult, and why?

Subject	Response
1	Picking the tool off velcro holder was difficult because the robot hand could not support a strong grasp of the object. Picking the tool out of the cabinet and putting the tool into the cabinet were difficult because the view was occluded. Reorienting the tool was difficult because of its size and shape
2	Horizontal tool insertion – cannot see around hand. Placing tool on station – placement was too low
3	Removing and replacing the tool from the cabinet. Difficult to handle the small parts and hold your grip. Also, difficult to see around DART huge circuit boards on the hands
4	Placing/removing tools from cabinet; poor viewing, lack of hand dexterity. Placing tools onto velcro; too small of a landing surface, wrong shape, poor hand dexterity

10) Which sections, if any, did you find easy, and why?

Subject	Response
1	Opening cabinet doors was easy due to previous experience/practice. Sliding latch was easy and involved only gross motions
2	Sliding tool capture latch – one finger task. Opening doors, I've done it a lot
3	Opening/closing doors and latches. Possibly because these tasks did not require fine movement or positioning. You could use any part of the hand to push the doors open
4	Opening the doors and opening the latches. The views were good and didn't require fine manipulation

11) Did you find that the more times you did the task that it's level of difficulty:

Response	Subject responding
Increased	1
Remained the same	2,3,4
Decreased	

12) Please explain the above response

Subject	Response
1	Difficulty of the task decreased at first due to initial learning but then slowly increased due to operator fatigue
2	Small tools are difficult to hold and maneuver
3	I did not plan the task before I grabbed he tool, therefore it was just as difficult the first time as it was the last time. Planning how the tool was oriented would have made a big difference in my case

4	How the tool was initially grabbed and the hands calibrated mattered so much that it was tough to improve

H.3 Section 3 Display Evaluation

1) Please comment on the overall usefulness of the display:

Collision Avoidance

Subject	**Response**
Not at all useful	
Somewhat useful	1,2,4
Very useful	3

2) If you chose to use the collision avoidance display, when did you use the display?

Subject	**Response**
1	When reorienting arms relative to body to increase dexterity near an objective
2	When reaching far out. Mostly used to obtain pose data
3	Base rotation, gross movements
4	Through both experiments

3) Did you ever leave it in the helmet field of view and not utilize it?

Subject	**Response**
1	Yes, I didn't use it for most of the task because concentrating on it would have detracted from my attention to the task
2	Yes
3	Yes, during fine movements. Sometimes I would forget it was there, probably because I was not used to using it
4	Yes

4) What about the display did you find useful or useless?

Subject	**Response**
1	It was useful to have a depiction of arm-base orientation so that I knew how to adjust the pose for improved range/dexterity. Collision avoidance was less useful because it didn't advise me of where the contact was likely to occur (other than upper arm vs. forearm) or how to avoid it, also there was no detection running for the hand
2	Pose data useful. Collision avoidance was marginally useful
3	Changing color to indicate proximity was very helpful
4	Having a view of the arm configuration is extremely helpful. It aided knowing how to position the shoulders for best dexterity. The collision avoidance displays didn't do much. It was never clear what was close

5) What improvements can you suggest to such a display?

Subject	Response
1	Add collision avoidance for hands. Use a small arrow to indicate where contact is imminent and in what direction it will react against the arm
2	Put it in both eyes. Move the display more to the right. A simple 2 stick or 3 stick model would do
3	
4	Key elements of environment

6) Should a collision avoidance display be presented visually or through a different modality?

Subject	Response
1	Visual is best
2	Collision avoidance should pinpoint the potential collision area, not just light up the whole joint
3	Visual. Audible alerts are very distracting. However, sometimes you get so focused on the task you might not notice the display. Maybe an audio would be helpful at critical times or within a certain proximity
4	Visually is good

7) If you did not use the collision avoidance display, why not?

Subject	Response
1	Sometimes it was obscured in the corner by the VR helmet eyepiece structure. Often I had to concentrate on the immediate task and not on supporting information or secondary objectives
2	Gave info that was distracting and not useful i.e. shoulder joint always red during tool task
3	When I was not using the display I would have to pause and look at the robot to determine my position. Probably contributed to my fatigue
4	N/A

8) How did you determine the position of your body relative to other objects?

Subject	Response
1	Looking down through robot eyes at robot arms or by consulting collision avoidance display
2	Look around
3	Pause and look
4	

H.4 Section 4 Comments

1) Please comment on the way in which you dealt with the time delay in this situation

Subject	Response
1	Move slowly and deliberately to see effects of robot response. Usually I would not wait for display update unless I was required to; instead I used it

	for quick reference and then returned to body view
2	Move slowly. Check environment frequently by looking around
3	I made very small movements then held that position until the display updated
4	I used the position control equivalent to the jog and wait method of the teleoperator. Slow movements also help

2) It is estimated that the IVA to EVA data link may have as much as a 0.5 second delay on the station. If this is the case, what methods could be incorporated that would help the operator in the presence of such a delay?

Subject	**Response**
1	Predictive displays; training with displays in place; independent faster links for other info (video/audio)
2	Real time updates to predictive displays
3	Practice very small smooth movements
4	Training, training, training

3) Please comment on any aspect if the experiment that you wish to elaborate on, suggestions you may have or comments.

Subject	**Response**
1	The ORU task consisted of gross motions and movements in an uncluttered workspace while the tool task consisted of dexterous motions in a cluttered cramped workspace. The two tasks provided good contrast
2	Testing involved a lot of arm and body motion that would be a lot easier with wider fields of view equipment
3	
4	I really liked having the collision overlay so the arm pose could be known. Similar displays with a virtual close-up of the work area would have greatly helped with the tool task. The DART system has a tough time doing very fine tasks with small tools. It's much better suited for gross manipulation tasks.

Appendix I KC-135 Data

I.1 KC-135 Experimental Methods

Each year high school students from all parts of Texas participate in the JSC Texas Fly-High program. This program allows students the unique opportunity to participate in current NASA research within the weightless environment of the KC-135 aircraft. As a mentor of a high school team in April 2001, the Robonaut simulation was flown on-board the KC-135 and experiments were conducted to investigate the effect of weightlessness on telerobotic performance. The outreach program imposed many restrictions on the experiment, including time, space and subject/personnel limitations. Lessons learned from the flight experiments aided in refining the protocol for the larger and more extensive laboratory trials. The following chapter describes the experimental methodology each of the three experiments.

It is hypothesized that the hardware and methodology that is used for telerobotic operations testing on Earth must be modified to take into account the effects of zero-G on a human operator before that hardware is used for space flight. The goal of the KC-135 experiment is to have students perform a series of telerobotic tasks using immersion hardware and software both in-flight, and on the ground, and to observe the differences in performance between the two conditions. The zero-G environment on the aircraft is a result of the aircraft's parabolic flight path. Figure I.1 shows the flight path for a single zero-G maneuver. Each student flight is comprised of 30 parabolas that deliver approximately 25 seconds of zero-G each.

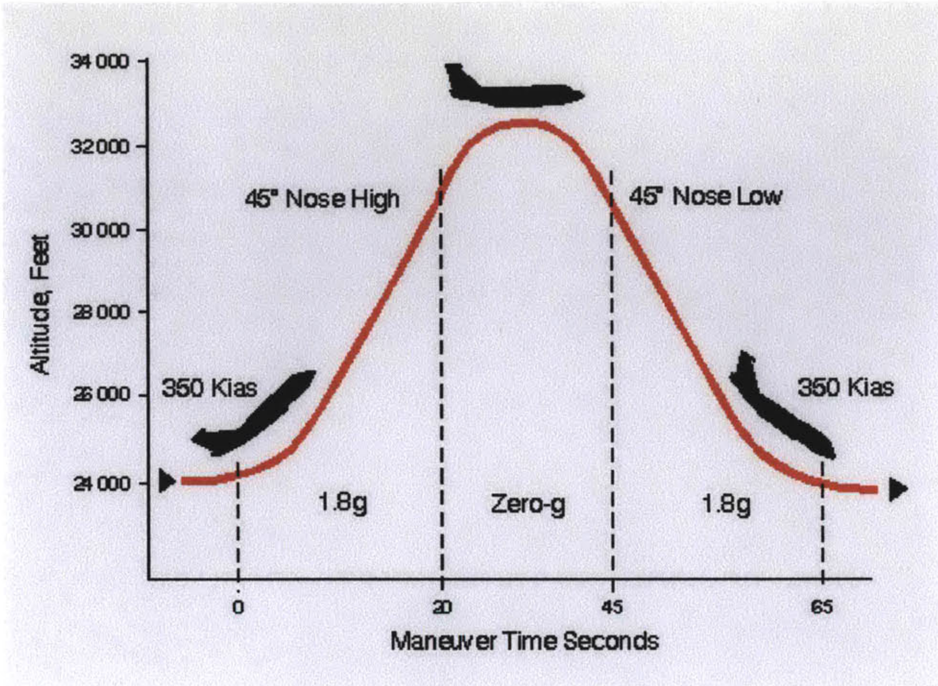


Figure I.1 Parabolic flight path of the KC-135 aircraft

Additional limits are placed on the space available for equipment and the number of crew allowed per flight. For each of the two flight days, 2 students and one mentor may fly. Therefore the experiment was restricted to one subject, one student computer operator and one mentor for each flight day to allow for maximum repeatability of results over the course of the 30 parabolas.

I.1.1 Experimental Set-Up

The laptops, HMD and Polhemus sensors were used to command the simulation on the KC-135. Figure I.2 shows a schematic of the experiment hardware and software connections that were flown on the KC-135 Aircraft. Figure I.3 and I.4 show photographs of the subject and experiment layout, respectively, taken during the first flight day. Note that in Figure I.3, the lexan support is covered in orange foam to protect airborne occupants from injury. The second flight photograph shows the manual basis task panel test. The subject wears the Polhemus hand tracker in both cases so that their trajectories can be recorded for later comparison. Note that the subject is not wearing the

CyberGlove during the trials. Throughout the trials the simulation renders the hand in a fixed position with the index finger pointed. The subject therefore, does not need to continually command the hand position with the CyberGlove.

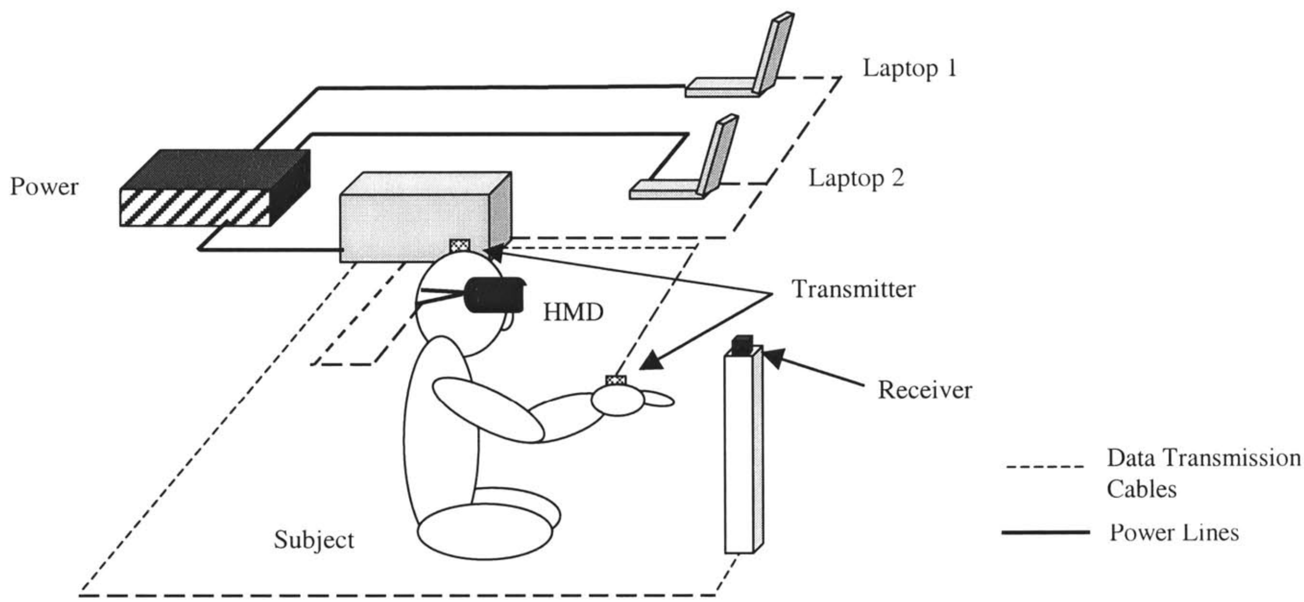


Figure I.2 KC-135 experiment layout schematic

Figure I.3 KC-135 simulation experiment photo

Figure I.4 KC-135 manual experiment photograph

I.1.2 KC-135 Experimental Protocol

The experimental protocol was run in-flight, and post-flight on the ground. The three-person team consisted of one subject, one computer operator and one experiment coordinator. The computer operator was responsible for saving the data for each trial, and changing the virtual task panel between tapping and tracing tasks. The experiment coordinator called out the next trial for both the subject and computer operator, kept time for starting and stopping each trial, and took data from the subject such as number of taps/traces completed, and subjective comments. In the event that one of the team members became ill during the flight, each person was trained for all jobs so that a substitution could be made at any point. The two subjects were females (age 17) and due to an in-flight illness and substitution, one male, age 39. None of the six team members had any prior KC-135 experience.

Over the course of the 30 parabolas, 26 were scheduled for trials. Two parabolas were required for equipment set-up and system ready checks, and two parabolas were designated spares in the event that a mistrial or error occurred that would require a re-start at the next parabola. The basis task panel (described in Chapter XX, Robosim Evaluation) is the hardware for the manual task, and the virtual task panels and HMD are used for the simulation tasks. For the tapping basis tasks, subjects are instructed to begin each trial at the center and tap with their right hand between like colors for 25 seconds. 25 seconds is the maximum amount of 0-G time afforded by one parabola. For the tracing basis task, subjects are instructed to trace the pattern continuously for 25 seconds. Subjects were trained in both tasks before the flight and given approximately 20min of practice with the task panels and hardware. For ease of hardware manipulation on the aircraft, the simulated tasks are completed first, followed by the manual tasks. At the end of the simulated trials, the subject removes the HMD and secures the manual task panel against the lexan stand. The task panel is two-sided and secured with Velcro. The simulated and manual tasks were repeated on the ground post-flight and finally, a subjective questionnaire was administered.

Between the tapping and tracing panels, there were 8 possible tasks for each parabola – one for each of the tapping colors: Red, Orange, Yellow, Green, Blue or Violet (R, O, Y, G, B, V) and one for each trace direction for the square Clockwise or Counterclockwise (CW, CCW). For 26 parabolas, 16 are simulated and 10 manual. For the 16 simulated runs, each of the 8 tasks is performed twice. For the 10 manual runs, the CW, CCW, R, O, and G tasks are completed twice each. The procedures for the trials is as follows for the different phases of flight:

1.8G Phase: Experiment coordinator calls out next task color/direction
Computer operator changes simulated task panel if necessary
Subject changes manual task panel if necessary
Computer operator names and opens next file
Subject rests – resets to starting hand position

0-G Onset: Experiment coordinator signals start

Computer operator begins file save

Subject begins task

Experiment coordinator notates trial

0-G End: Experiment coordinator signals stop

Computer operator stops file save

Subject ends task

Experiment coordinator records number completed and final subject comments

Data recorded included number of taps completed, number of square segments completely traced, and joint angle data for the arm and head. During flight day two the subject became ill and needed to be removed from the experiment. The experiment coordinator resumed her place after trial seven, completed 8 simulated trials and 10 manual trials.

I.2 KC-135 Results

There were two subjects for these experiments, however due to nausea, another team member replaced one of the subjects during the trials, thereby creating a third subject. For this reason, there is only ground data for Subject 2 (no flight data due to illness). For Subject 3 there is only manual flight and manual ground data (no simulation trials), as the Subject 3 changed places with Subject 2 the during the simulation trials. Subject 2 believes she became ill since was unable to determine her orientation while in the zero-G phase while wearing the HMD, stating that she felt as if she were immediately inverted. Since her view of the aircraft was occluded by the HMD, the subject only had proprioceptive and vestibular cuing during the positive-G phases of flight. Once the zero-G onset occurred, the subject could no longer rely on those vestibular and proprioceptive cues. The lack of any visual information to confirm that she was upright, created spatial disorientation and motion sickness ensued. Due to the small number of subjects and the irregularity of the protocol on the second day, no statistical analysis can be performed on this data. However, subjective responses and observations from the trends in the data can provide some clues into how the teleoperator behaves in microgravity.

Figure I.5 compares the average ground data with the average flight data for Subject 1's manual task trials. Figure I.6 shows similar data for Subject 3

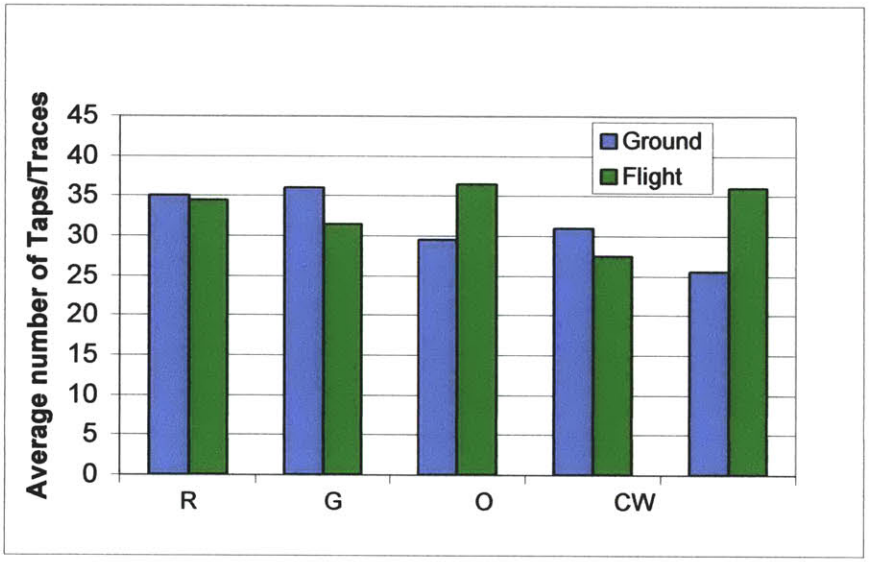


Figure I.5 Manual Average Tap/Trace Data for Subject 1

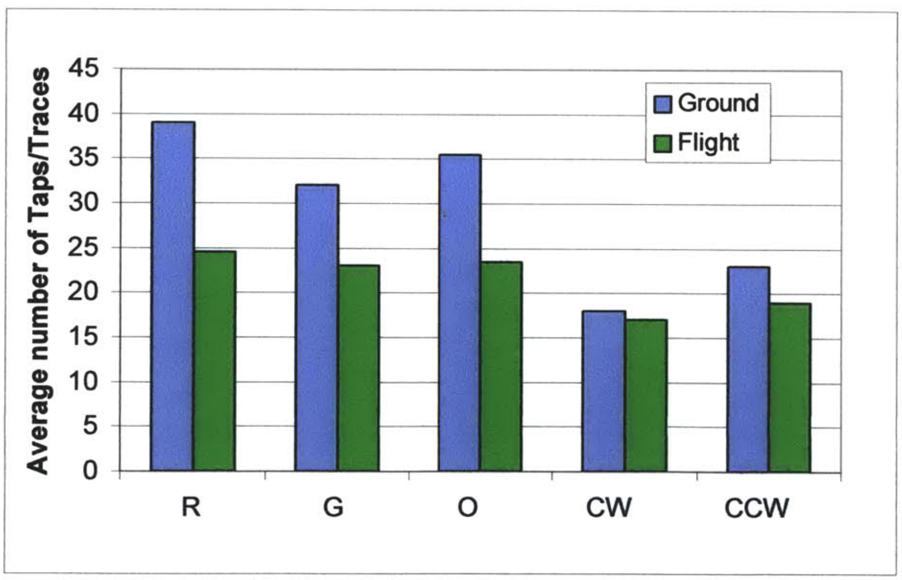


Figure I.6 Manual average tap/trace data for Subject 3

Recall that the red (R) and green (G) targets are the innermost horizontal and vertical targets, respectively, followed by the orange (O) in the horizontal direction. CW and CCW denote the tracing directions. Subject 1 showed an improvement with the Green targets averaging 4.5 more taps on the ground than in flight, but showed no difference with the Red targets. Orange taps slowed in flight by an average of 7. Clockwise traces slowed in flight an average of 3.5 traces while Counter-clockwise increased in flight by an average of 10.5. Subject 3 showed a slight to moderate decrease for each task. Red flight taps decreased by an average of 14.5, Green by an average of 12.5 and Orange by an average of 8.5. The manual modality is meant to act as the baseline comparison between flight and ground conditions. With data from only two subjects, no conclusions can be drawn from these results, although a slowing trend in flight is visible for Subject 3.

Figure I.7 shows the simulation data for Subject 1. There were two in-flight errors during the first Yellow trial and the first Clockwise trial. In both cases, the subject could not locate their virtual hand in the virtual scene since the Polhemus receiver was brought too far from the transmitter during the task and signal was lost. With the exception of the Violet targets, again all in-flight values were equal or lower than ground values, most significantly for the Clockwise and Counter-clockwise tracing task.

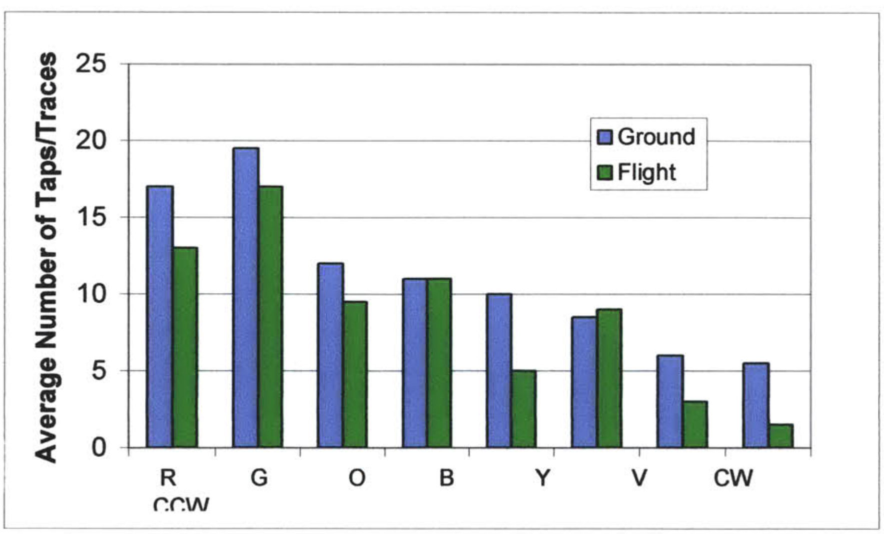


Figure I.7 Simulation average tap/trace data for Subject 1

In the Subjective responses, both subjects indicated that Polhemus tracking was difficult, specifically finding their hand in the scene. Both subjects noted that the straps were insufficient to keep them stable and as a result, tended to be tipped forward into the transmitter during the zero-G phase. This prevented them from having adequate room to translate their hand. They also remarked that there was difficulty in translating in a straight line in zero-G, affecting their tracing tasks. Again, due to the limited sample, it is difficult to determine or separate the effects of zero-G from the effects of the Polhemus tracker.

I.3 KC-135 Experiment Discussion

It was fortunate that an opportunity presented itself to study the effects of microgravity on human teleoperation performance. The KC-135 Texas-Fly High program however, presented many restrictions on the protocol and therefore level and amount of repeatable data that could be obtained. Within the discipline of human space flight experiments, large numbers of experimental subjects are difficult to come by and have traditionally been limited to the number of Skylab, Space Shuttle, Space Station and MIR crewmembers willing and available to participate. This limitation makes the transference of results obtained to the larger population difficult at best. In the same vain, in these experiments, the already minimal number of subjects was further depleted due to in-flight illness. For this reason, no conclusive results can be gleaned from the collected data. The lessons learned and subjective comments can however, be utilized to aid in further experimental design and future work.

The overriding obstacles that subjects overcame while performing the experiment in the microgravity environment were posture control and Polhemus tracking. The straps used to hold the subjects in place were insufficient for controlling their posture and as a result they would "float" out of the range of the Polhemus sensor. Each subject adapted his or her own strategy for keeping stable during the trials. In microgravity, the Polhemus sensor did not behave as it did on the ground. A verification test was performed in the weeks prior to the flight with the Polhemus mounted in the KC-135 while the aircraft was on the ground. There was no evidence in the data to indicate interference from the aircraft itself. The primary difference between the in-flight and verification test was that the verification test was conducted in the center of the aircraft hull, yet it was not until the day of the flight that the final location for our experiment was determined by the flight director. As it happened, our group was placed in the front of the aircraft, closest to the cockpit near an approximately 6ft long and 4ft high metal component rack (see Figure 5.4). In addition, for safety reasons, the verification test was performed while the aircraft sat un-powered on the tarmac. It is hypothesized that the presence of the large amount of metal nearby and possible interference with the powered aircraft systems led to the reduced tracking envelope of the magnetic Polhemus sensor.

The inability for the subjects to "keep track" of their hand in the scene led them to make slower movements. Often for the targets farthest from the center of the board,(particularly the yellow targets) nearing the operating envelope of the sensor, the hand would drift without command from the subject. This happened most notably between trials when during the 2-G phase, the simulation was not switched off but the subject would rest their hand far out of range of the sensor, making it hard to recover the position of the hand and arm once the trial began. Subjects each developed their own strategies for coping with this phenomenon, the most successful of which was resting their non-sensor arm (left arm) on the sensor cube and resting their sensor arm (right arm) on top of that – keeping it in the field of view of the helmet.

The subjects remarked after the experiment that they wished they had completed all of the manual trials before the simulation trials so that they could become comfortable with the task before attempting it in the aircraft environment. Likewise it was determined that performing the simulation tasks before the robot tasks would allow the subject not only time to learn the task, but to learn about the operating characteristics (kinematics, joint limits, rate limits, collision limits, etc.) of the robot before operating it for the first time. For this reason and other safety concerns, it was determined to run the laboratory experiment with manual trials followed by simulation trials followed by robot trials.

I.4 Supplemental Data

The following tables list the data obtained during the KC-135 flight experiments. Table I.1 displays the flight data for subject 1 labeled by trial, task panel (tapping dots or tracing squares), the color or direction for that trial, and the number of taps or traces completed. Tables I.1 and I.2 lists the flight and ground data for subject 1. Tables I.3 and I.4 show the flight and ground data for subject 3, respectively. Note that in all tables the first 16 trials (the green shaded trials) are simulation trials, and trials 17-26 (shaded yellow) are manual trials.

Table I.1 Flight data for Subject 1

Trial	Panel	Color/Direction	# Taps/Lines
1	tap	B	6
2	tap	G	17
3	tap	Y	ERR
4	tap	R	17
5	trace	CW	ERR
6	trace	CCW	2
7	tap	O	13
8	tap	V	9
9	trace	CW	3
10	tap	V	9
11	tap	G	17
12	tap	R	9
13	tap	Y	5
14	tap	O	6
15	trace	CCW	1
16	tap	B	16
17	tap	G	30
18	tap	R	34
19	trace	CW	23
20	trace	CCW	32
21	tap	O	36
22	trace	CW	32
23	tap	G	33
24	tap	R	35
25	tap	O	37
26	trace	CCW	40

Table I.2 Ground data for Subject 1

Trial	Panel	Color/Direction	# Taps/Lines
1	trace	CW	5
2	tap	V	7
3	tap	R	15
4	tap	Y	8
5	trace	CCW	4
6	tap	B	7
7	tap	G	18
8	tap	O	13
9	trace	CCW	7
10	tap	R	19
11	tap	V	10
12	tap	Y	12
13	trace	CW	7
14	tap	O	11
15	tap	B	15
16	tap	G	21
17	tap	G	36
18	tap	R	36
19	trace	CW	37
20	tap	O	30
21	trace	CCW	27
22	trace	CCW	24
23	tap	O	29
24	tap	R	34
25	tap	G	36
26	trace	CW	25

Table I.3 Flight data for Subject 3 – Manual Basis Tasks

Number	Panel	Color/Direction	# Taps/Lines
17	trace	CW	16
18	tap	G	26
19	tap	R	24
20	tap	O	24
21	trace	CCW	18
22	trace	CCW	20
23	tap	R	25
24	trace	CW	18
25	tap	O	22
26	tap	G	21

Table I.4 Ground data for Subject 3 – Manual Basis Tasks

Number	Panel	Color/Direction	# Taps/Lines
17	tap	O	32
18	tap	G	39
19	trace	CW	13
20	trace	CCW	22
21	tap	R	39
22	tap	G	41
23	tap	R	39
24	trace	CW	23
25	tap	O	32
26	trace	CCW	24

The following tables arrange the data such that the flight and ground performance can be compared. Table I.5 and I.6 shows the data for subjects 1 and 3, respectively. Note that each task was repeated twice per condition (flight or ground) and are labeled as Condition1, Condition 2. The average numbers of completed taps or traces for a particular task are compared in the final column.

Table I.5 Flight and ground comparison for subject 1

SIMULATED BASIS						
Task	**Flight 1**	**Flight 2**	**Ground 1**	**Ground 2**	**Average Flight**	**Average Ground**
R	17	9	15	19	13	17
O	13	6	13	11	9.5	12
Y	ERR	5	8	12	5	10
G	17	17	18	21	17	19.5
B	6	16	7	15	11	11
V	9	9	7	10	9	8.5
CW	ERR	3	5	7	3	6
CCW	2	1	4	7	1.5	5.5
MANUAL BASIS						
Task	**Flight 1**	**Flight 2**	**Ground 1**	**Ground 2**	**Average Flight**	**Average Ground**
R	34	35	36	34	34.5	35
O	36	37	30	29	36.5	29.5
G	30	33	36	36	31.5	36
CW	23	32	37	25	27.5	31
CCW	32	40	27	24	36	25.5

Table I.6 Flight and ground comparison for Subject 3

MANUAL BASIS						
Task	**Flight 1**	**Flight 2**	**Ground 1**	**Ground 2**	**Avg Flight**	**Avg Ground**
R	24	25	39	39	24.5	39
O	24	22	32	32	23	32
G	26	21	39	32	23.5	35.5
CW	16	18	13	23	17	18
CCW	18	20	22	24	19	23

Appendix J KC-135 Subjective Responses

The following questionnaires were administered to the KC-135 subjects. The first section contains the questions and responses for the common ground and flight questions. The second section contains the responses to the specific flight questions that were not relevant to the ground testing.

J.1 Ground Test Subjective Questionnaire

J.1.1 Fatigue Questions

1) Did you experience any fatigue during the trials? No Fatigue; Some Fatigue; Major Fatigue

Subject	Ground	Flight
1	Some Fatigue	No Fatigue
2	No Fatigue	Major Fatigue
3	Some Fatigue	Some Fatigue

If so, where (on body, or mental) and at what point during the test did this occur?

Subject	Ground	Flight
1	During the simulation with the helmet I felt my back [getting] tired	
2		On the 5th or 6th run I wasn't able to adapt
3	Arm	Pointing arm

2) What methods did you use to combat fatigue during the trials?

Subject	Ground	Flight
1	Stretched	None
2	I placed my hand on my lap when each trial was over and stayed calm to try not to hurry	I tried lying down and sitting
3	Rest in between sets	Hold arm, rest arm

3) Do you think that any aspects of the fatiguing effects will be better or worse in a reduced gravity environment?

Subject	Ground	Flight
1	Better	

2	Worse. The accuracy would be affected and more time would be wasted	
3	Arm fatigue less	

4) Did you experience any physical discomfort during the trials? If so, please describe:

Subject	**Ground**	**Flight**
1	No	No
2	None	The helmet caused me to think that I was upside down, not just floating around so it caused me to become nauseous as we changed G forces
3	No	Mild nausea

J.1.2 Specific Task Questions

1) Please rate the overall difficulty of the **TAPPING** task, 1 being Very Easy and 5 being Very Difficult:

Subject	**Ground**	**Flight**
1	1	2
2	4	3
3	1	4

2) Please elaborate on the level of difficulty (choose one):

Subject	**Ground**	**Flight**
1	The entire task was easy	A few parts of the task were difficult, but most of the parts were easy
2	Most of the task was difficult, only a few parts were easy	Half of the task was easy, half difficult
3	The entire task was easy	Most of the task was difficult, only a few parts were easy

3) Which sections of the task did you find difficult and why?

Subject	**Ground**	**Flight**
1	Not going through the board	Keeping myself stable and not floating away
2	The accuracy in the tapping of the bottom that were farthest from the center – took more time and effort	Trying to concentrate wasn't hard, being nauseous was
3	No section	Finding hand in screen

4) Which sections of the task did you find easy, and why?

Subject	Ground	Flight
1	Pointing to the right colors	Finding my board and hand because I had it set to where I could see both
2	The closest buttons because I didn't lose the close perspective vision. It was easier to [get] accustom[ed] to	Buttons
3	All – without helmet I could see	Manual test

5) Did you find that the more times you did the task that it's level of difficulty (circle one):

Subject	Ground	Flight
1	Decreased	Decreased
2	Remained the Same	Increased
3	Remained the Same	Decreased

5a) Please explain the above response:

Subject	Ground	Flight
1	Because you got more practice and was able to correct mistakes	You [know] what to expect and how to fix it
2	The level of difficulty decreased except for the accuracy. I wasn't able to improve that with the tracker	I wasn't able to take the G forces. Caused me to be dismissed from the experience
3	Easy tasks on the ground	Found hand, better adapted

6) Did you alter your strategy during the tapping task at all during the course of the day – please explain:

Subject	Ground	Flight
1	No	Yes, placed my right hand on my forearm during 2-G so that I can know where it's at during zero-G
2	I just placed my hand on my lap at times but there were times I just kept my hand in front of me	Couldn't adjust my hand movement. I didn't follow where my hand was so I had that rested
3	No –no need	No

7) Please rate the overall difficulty of the **TRACING** task, 1 being Very Easy and 5 being Very Difficult (circle one)

Subject	Ground	Flight
1	2	3
2	2	5
3	1	2

8) Please elaborate on the level of difficulty:

Subject	Ground	Flight
1	A few parts of the task were difficult, but most of the parts were easy	Half of the task was easy, half difficult
2	A few parts of the task were difficult, but most of the parts were easy	The entire task was difficult
3	The entire task was easy	The entire task was easy

9) Which sections of the task did you find difficult and why?

Subject	Ground	Flight
1	Keeping a straight line	Keep[ing] a straight line
2	Picking my hand up and replac[ing] it again and trace the blue when I was at purple	At that point I wasn't able to find my hand so that section I only [had] one chance to do it then I got sick
3	none	Find hand

10) Which sections of the task did you find easy, and why?

Subject	Ground	Flight
1	Recognizing colors because the[y] were very nice and bright	The manual
2	Not picking up my hand and follow[ing] the stripes because I adapted to the tracing faster	None
3	All – easy vision	Tracing

11) Did you find that the more times you did the task that it's level of difficulty (circle one)

Subject	Ground	Flight
1	Decreased	Decreased
2	Decreased	Increased
3	Remained the same	Decreased

11a) Please explain the above response:

Subject	Ground	Flight
1	Because you already know exactly what to do	Because I had a better sense of depth in how far the object was
2	Tracing was an easier task that can be improved in less time	I got sicker by the motion sickness of the helmet
3	Tasks in 1-G were easy	Learned

12) Did you alter your strategy during the tracing task at all during the course of the day – please explain:

Subject	Ground	Flight
1	No	No
2	I kept my hand paced low so there would be less mistakes	No
3	No	Yes, hold arm in place with other arm

J.1.3 Polhemus Questions

1) Did the Polhemus trackers track your movements adequately: Not At All, Some of the time, Half the time, Always

Subject	Ground	Flight
1	Most of the time	Most of the time
2	Most of the time	Some of the time
3	Most of the time	Most of the time

2) Did the above answer depend on the speed at which you were moving: Tracked the same no matter what speed I moved, Tracked better when I moved more slowly, Tracked better when I moved more quickly

Subject	Ground	Flight
1	Tracked better when I moved more slowly	Tracked better when I moved more slowly
2	Tracked better when I moved more slowly	Tracked better when I moved more slowly
3	Tracked better when I moved more slowly	N/A

3) Did the ability of the Polhemus to track depend on the movements you were doing? If so, describe the types of movements (straight line, curved, planar, etc.) that caused it to:

Track Well:

Subject	Ground	Flight
1		No, basically moved the same
2	It tracked well when I was tracing a straight line	Yes it did I just had to have my hand position on the right place
3		

Track Poorly:

Subject	Ground	Flight
1		
2	It tracked poorly when I changed	

	the direction when picking different targets on the squares	
3		

4) Please comment on any hardware problems that may have been experienced during the trials:

Subject	**Ground**	**Flight**
1	None	None
2	None	Thinking that I was upside [down] terminated my senses caused me to become sick
3	None	None

5) Please comment on any software problems that may have been experienced during the trials:

Subject	**Ground**	**Flight**
1	None	Too close to the transmitter
2	There were times when I was doing the squares and for a second the hand movement stopped while I was still moving, but I was not even moving at a fast pace	There was an error sign that came on, I don't know what that was about
3	None	

6) Do you feel that you had all of the information that you needed to complete the task?

Subject	**Ground**	**Flight**
1		Yes
2	I understood all the information, it was the skill of moving the tracker	Yes
3	Yes	Yes

7) Do you think a display would have helped complete the tasks? If so, please describe what information you would have liked in order to complete the task:

Subject	**Ground**	**Flight**
1		No
2	No, I had all that I needed	No
3		When the hand is thru the display

7a) If not, why not?

Subject	**Ground**	**Flight**
1		Everything was basically self-explanatory
2	The manual [trials] helped me complete the task because it was	I had all the knowledge that I needed

	like practice for it, but not having to do the [simulation] first left me with more mistakes in the beginning	
3		

I.1.4 Additional Comments

Please comment on any aspect of the experiment that you wish to elaborate on, suggestions you may have, or comments:

Subject	Ground	Flight
1		Everything was fine but a better transmitter that allows you to be farther away would have been nice
2	I think that the experiment would help with the Robonaut but the 30seconds that we get doesn't seem to help because the Robonaut goes slow[ly] to do anything	Wish that I could have done it again
3	Good environment. Manual task, helmet hard task	More practice, helmet made me nauseous, couldn't find hand

J.2 Flight Specific Questions

J.2.1 Physiology Questions

1) Did you experience any nausea during the flight?

Subject	Flight
1	No nausea
2	Significant nausea, significant vomiting
3	Mild nausea, no vomiting

2) Did you take the medication offered?

Subject	Flight
1	Yes – 1 tablet
2	Yes
3	Ye – 2 tablets

3) If so, how many minutes before the flight did you take the medication?

Subject	Flight
1	60
2	90
3	90

4) Did you consume breakfast this morning? If so, what did you eat/drink?

Subject	Flight
1	Yes, toast and apple juice
2	Yes, cork flakes
3	Yes, bagel w/cream cheese, juice, cereal, milk

5) Were you able to complete:

Subject	Flight
1	All of the trials
2	None of the trials
3	Most of the trials

6) How long did it take for you to feel adapted to the changing gravity environment of the aircraft?

Subject	Flight
1	Felt adapted immediately
2	Never felt adapted
3	Felt adapted after the first several parabolas

5) Did you find any parts of the task easy of difficult due specifically to 0-g or 2-G effects (please explain)?

Subject	Flight
1	Keeping stable during 0-G
2	0-G I wasn't able to be as fast as I was in the ground
3	In 0-G easy to hold arm, moving in 0-G was tough

J.2.2 Comparison Questions

1) Did you find overall:
   ____All aspects of the experiment were more difficult in the KC than on the ground
   ____Some aspects were more difficult in the KC
   ____The experiment was the same in the KC as on the ground
   ____Some aspects were easier on the ground
   ____All aspects were easier than on the ground

Subject	Flight
1	
2	All aspects of the experiment were more difficult in the KC than on the ground
3	All aspects of the experiment were more difficult in the KC than on the ground

1a) Please explain the above response:

Subject	Flight
1	
2	Being sick added too much difficulty for me to finish the experiment
3	Zero-g moved me around, need to be strapped better

Appendix K Basis Experiment Data and Supplemental Results

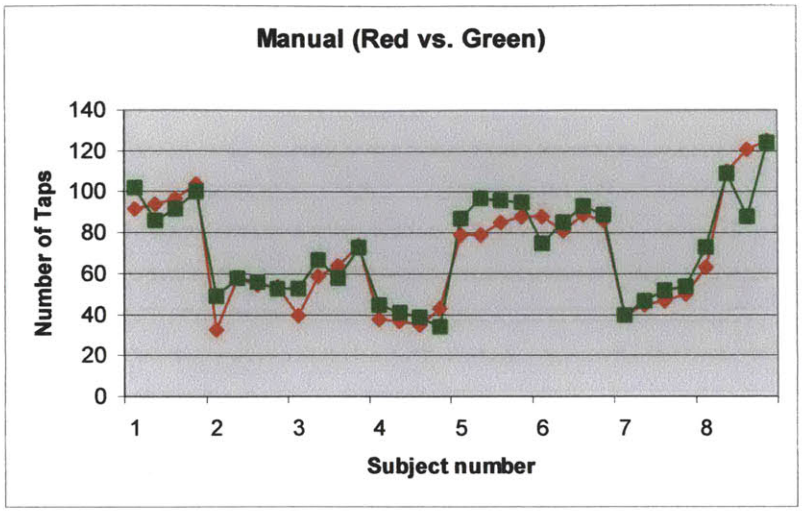
The following tables give the data for the percentage of basis task trials with errors:

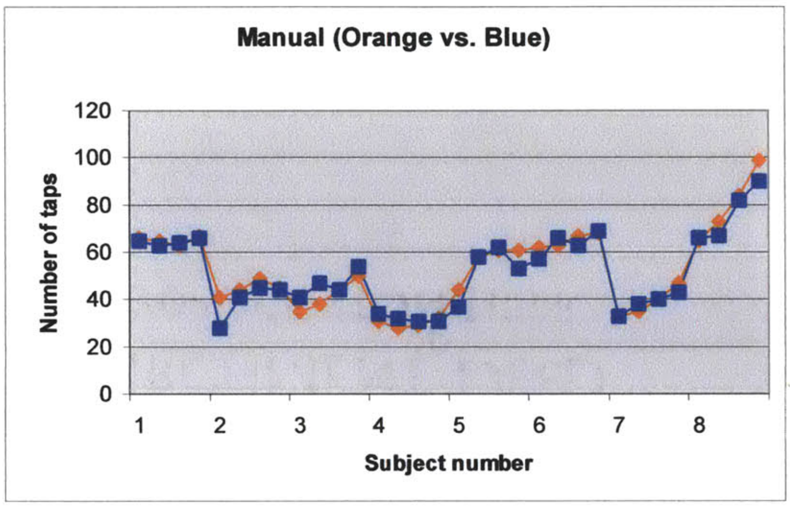
Table K.1 Trials with errors for basis task testing

%Trials w/Errors

	Subject	# w/error	total#trials	% w/error
man	1	4	32	12.5
	2	3	32	9.375
	3	0	32	0
	4	4	32	12.5
	5	5	32	15.625
	6	10	32	31.25
	7	7	32	21.875
	8	12	32	37.5
			man avg	**17.57813**
sim	1	7	32	21.875
	2	17	32	53.125
	3	2	32	6.25
	4	12	32	37.5
	5	6	32	18.75
	6	10	32	31.25
	7	20	32	62.5
	8	22	32	68.75
			sim avg	**37.5**
robot	1	8	32	25
	2	2	32	6.25
	3	3	32	9.375
	4	2	32	6.25
	5	1	32	3.125
	6	4	32	12.5
	7	21	32	65.625
	8	18	32	56.25
			robot avg	**23.04688**
				19.53125
	total	**200**	**1024**	

Figures K.1 thru K.3 show the correlation between targets of like distances in each of the three modes. .





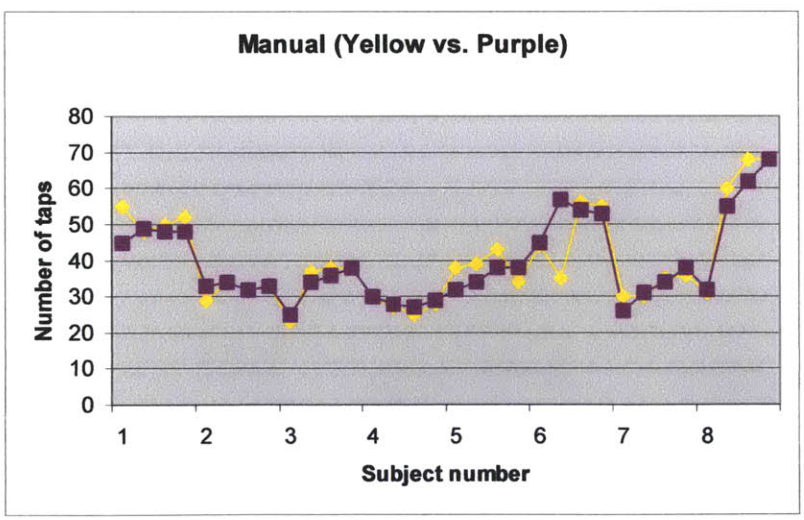
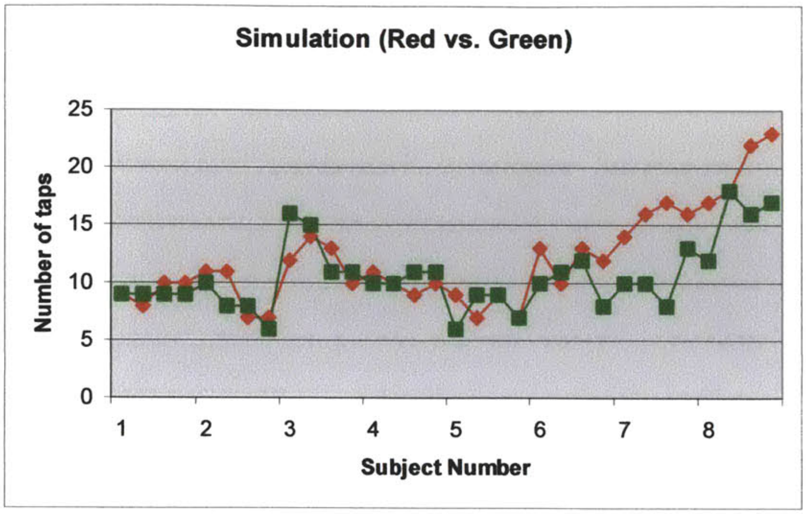
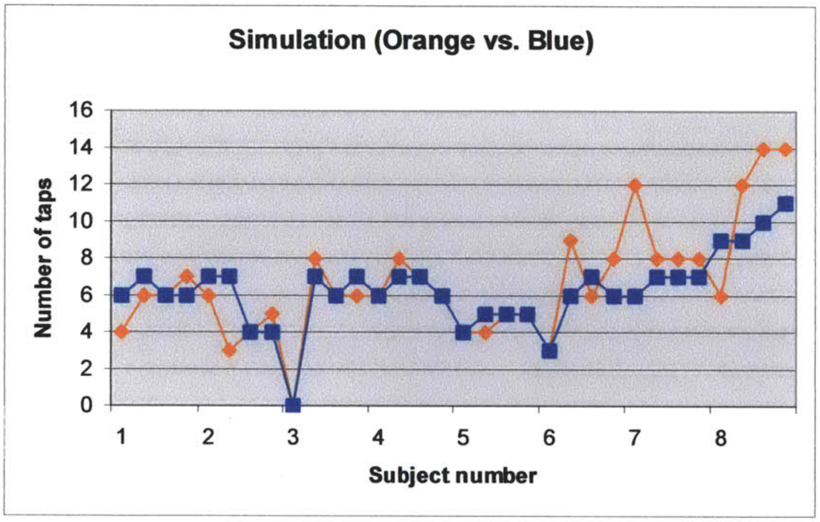


Figure K.1 Number of taps per subject for the Manual mode





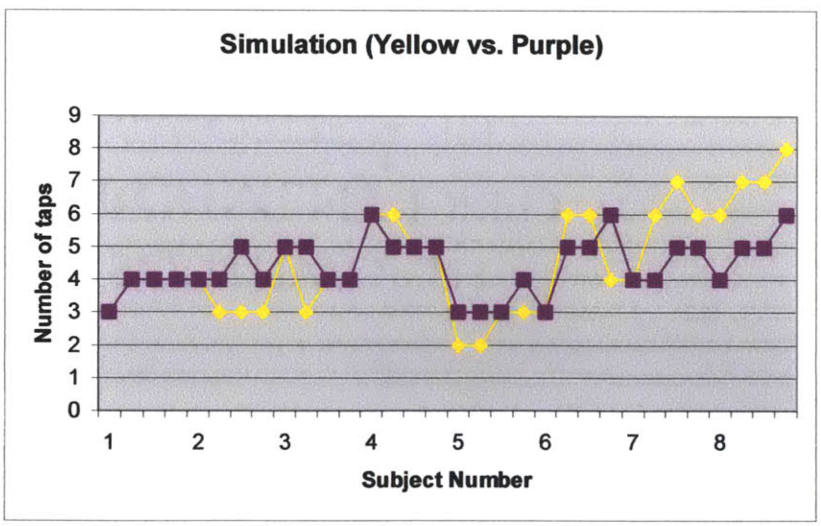
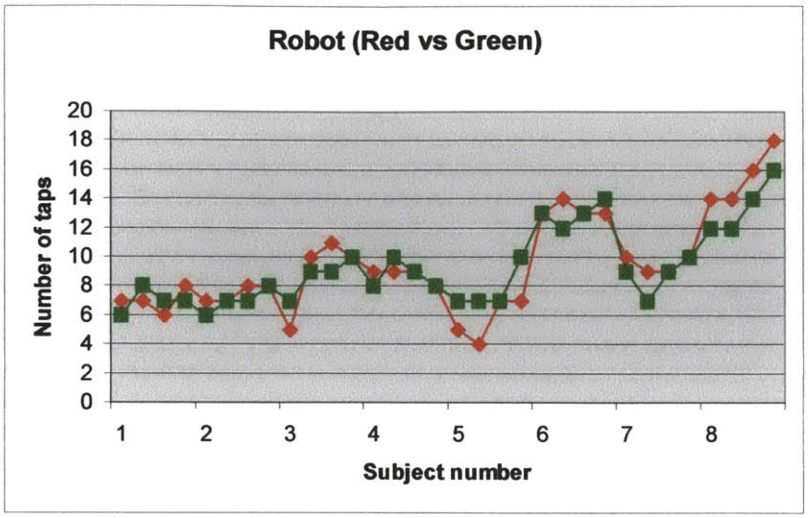
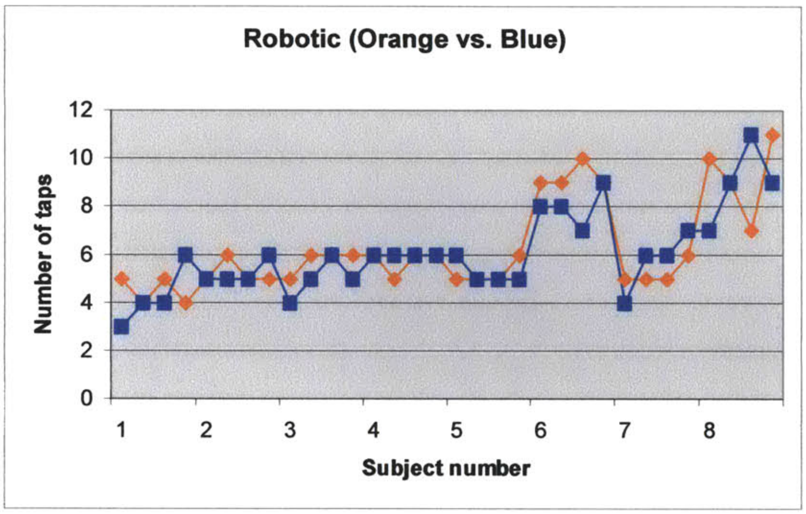


Figure K.2 Number of taps per subject for the Simulation mode





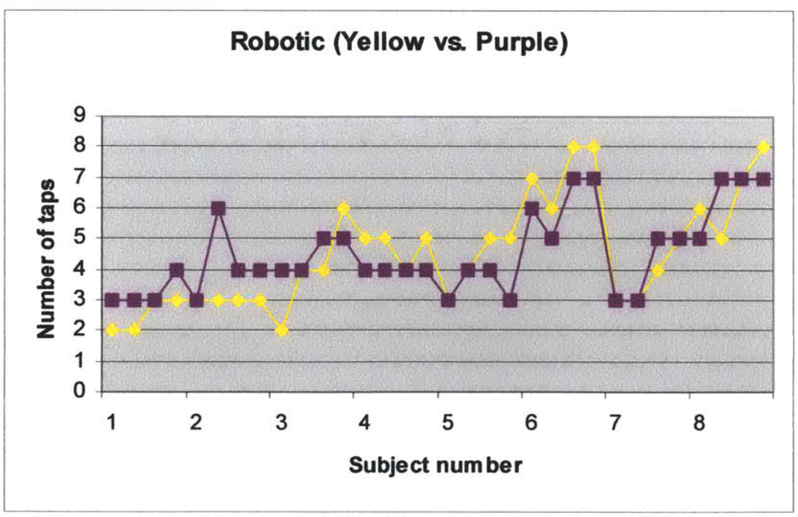
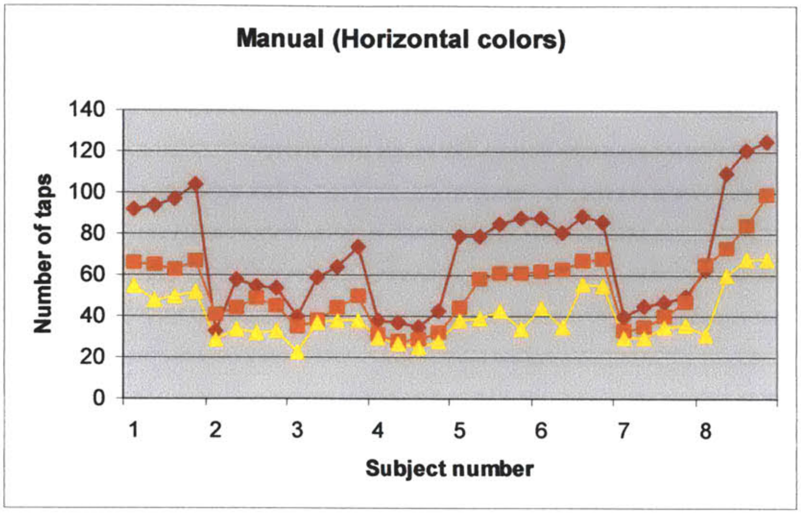
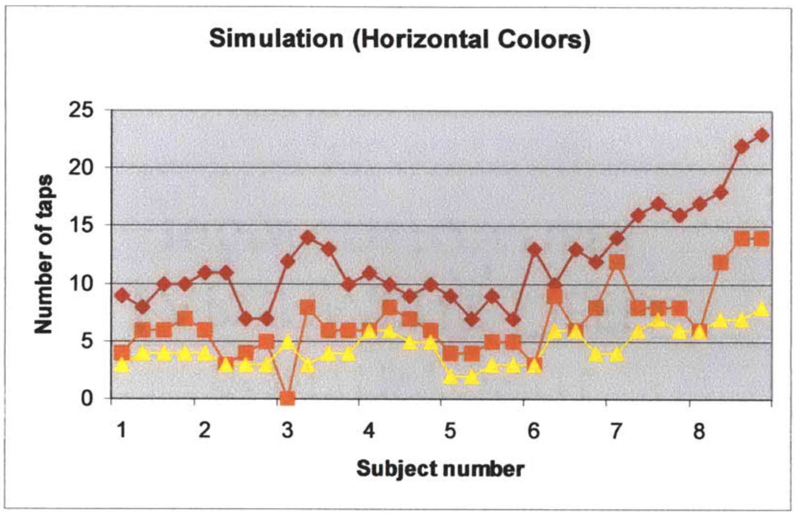


Figure K.3 Number of taps per subject for the Robotic mode

Figures K.4 and K.5 compare the horizontal and vertical target tapping performance, respectively, for each subject





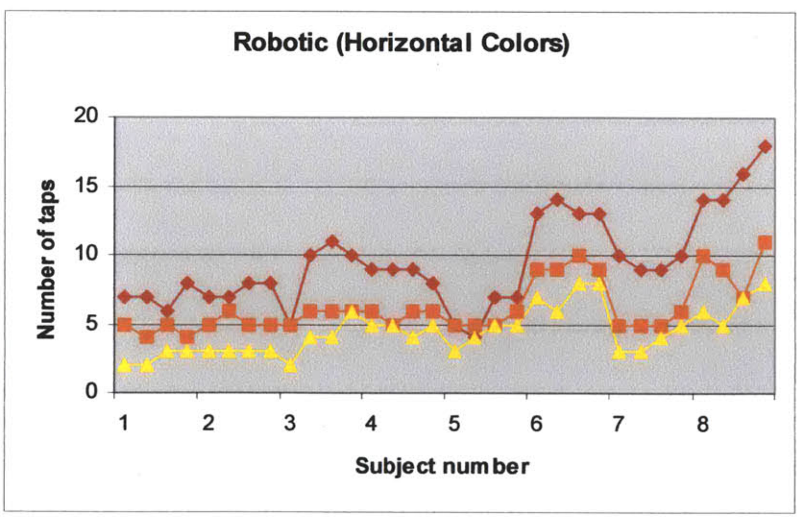


Figure K.4 Comparison of horizontal targets across modality

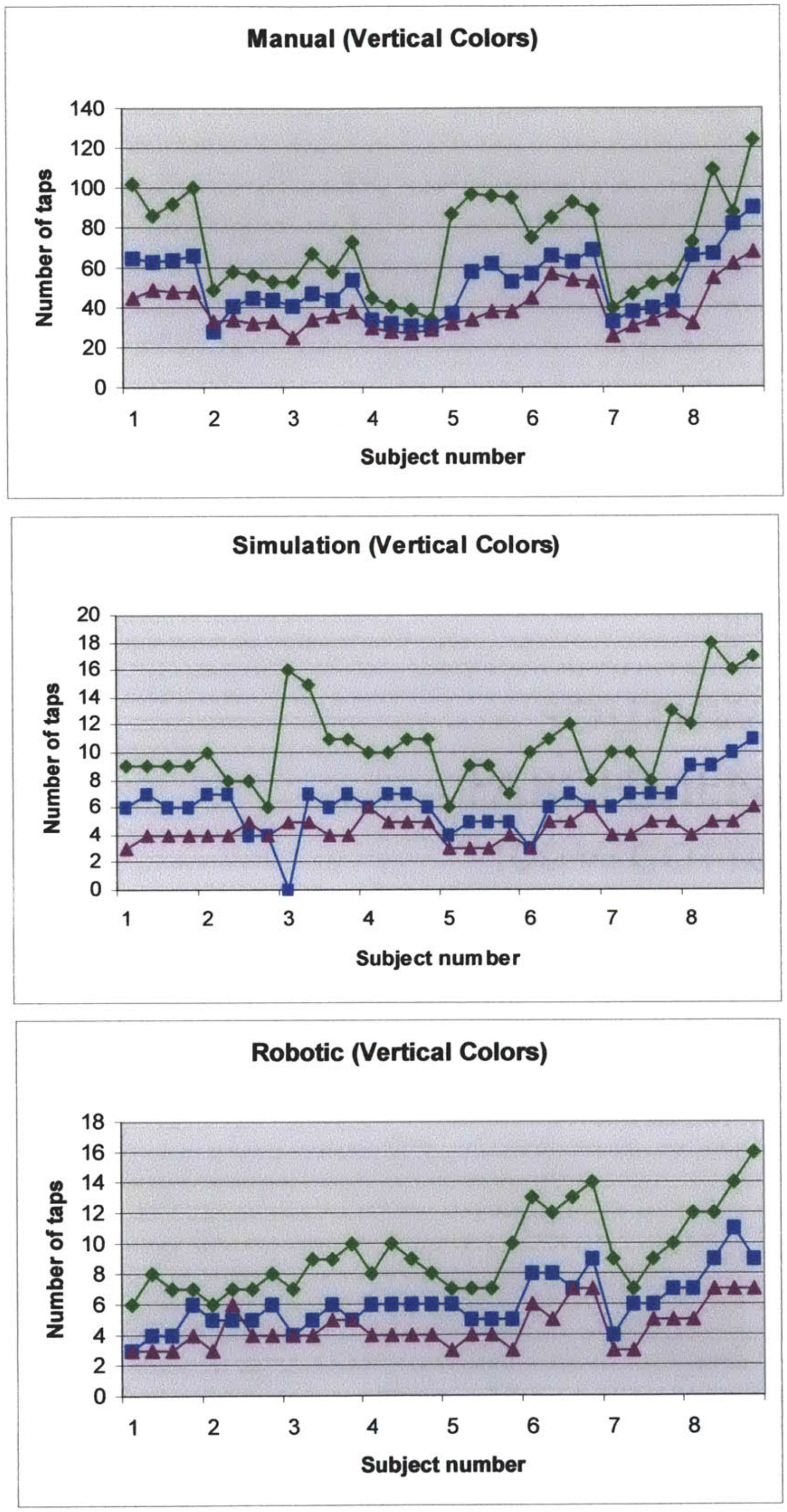


Figure K.5 Comparison of vertical targets across modality

The following tables (K.2 through K.9) list the results of the gender effect ANOVAs for the three modalities Probability values in bold are statistically significant.

Table K.2 Gender effects for red taps

RED						
MAN	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	61.0625	586.7292	4.462449	**0.043081**
	Male	16	79.75	665.4		
SIM	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	15	10.13333	3.980952	6.615258	**0.015708**
	Male	15	13.33333	19.2381		
ROBOT	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	8.0625	2.4625	7.477996	**0.01038**
	Male	16	11	16		

Table K.3 Gender effects for orange taps

ORANGE						
MAN	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	45.4375	184.2625	6.909635	**0.013387**
	Male	16	60	306.8		
SIM	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	14	5.857143	2.131868	2.886904	0.100798
	Male	15	7.466667	10.55238		
ROBOT	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	5.3125	0.495833	10.92873	**0.002461**
	Male	16	7.25	5		

Table K.4 Gender effects for yellow taps

YELLOW						
MAN	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	36.1875	100.9625	3.429109	0.073922
	Male	16	43.875	174.7833		
SIM	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	4.125	1.05	2.491525	0.124948
	Male	16	5	3.866667		
ROBOT	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	3.5625	1.4625	12.07513	**0.001578**
	Male	16	5.4375	3.195833		

Table K.5 Gender effects for green taps

GREEN

	Gender	n	Average	Variance	F	P-value
MAN	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	62.875	473.05	5.470832	**0.026189**
	Male	16	81.5	541.4667		
SIM	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	10.1875	6.1625	0.569024	0.456528
	Male	16	11	12.4		
ROBOT	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	15	7.866667	1.695238	11.10769	**0.002428**
	Male	15	10.4	6.971429		

Table K.6 Gender effects for blue taps

BLUE

	Gender	n	Average	Variance	F	P-value
MAN	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	45.625	173.9833	5.329268	**0.028042**
	Male	16	57.75	267.4		
SIM	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	15	6.2	1.028571	0.621612	0.436847
	Male	16	6.6875	4.7625		
ROBOT	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	5.125	0.916667	12.45387	**0.001367**
	Male	16	7	3.6		

Table K.7 Gender effects violet taps

VIOLET

	Gender	n	Average	Variance	F	P-value
MAN	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	35.5625	62.12917	4.531141	**0.04161**
	Male	16	43.5625	163.8625		
SIM	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	4.4375	0.529167	0.039578	0.84365
	Male	16	4.375	1.05		
ROBOT	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	4	0.666667	5.536398	**0.025376**
	Male	16	5.0625	2.595833		

Table K.8 Gender effects for clockwise traces

CW	Gender	n	Average	Variance	F	P-value
MAN	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	16.9375	100.0625	20.35074	**9.23E-05**
	Male	16	32.0625	79.79583		
SIM	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	2.75	0.733333	2.142857	0.153635
	Male	16	3.25	1.133333		
ROBOT	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	15	2.533333	0.980952	3.257692	0.081855
	Male	15	3.266667	1.495238		

Table K.9 Gender effects for counter-clockwise traces

CCW	Gender	n	Average	Variance	F	P-value
MAN	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	16.75	78.33333	13.66618	**0.000872**
	Male	16	29.25	104.6		
SIM	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	1.6875	0.3625	0.916031	0.346169
	Male	16	1.9375	0.729167		
ROBOT	*Gender*	*n*	*Average*	*Variance*	*F*	*P-value*
	Female	16	1.375	0.25	5.248447	**0.029165**
	Male	16	2.1875	1.7625		

Figures K.6 through K.13 show the individual subject learning plots for the handrail tasks.

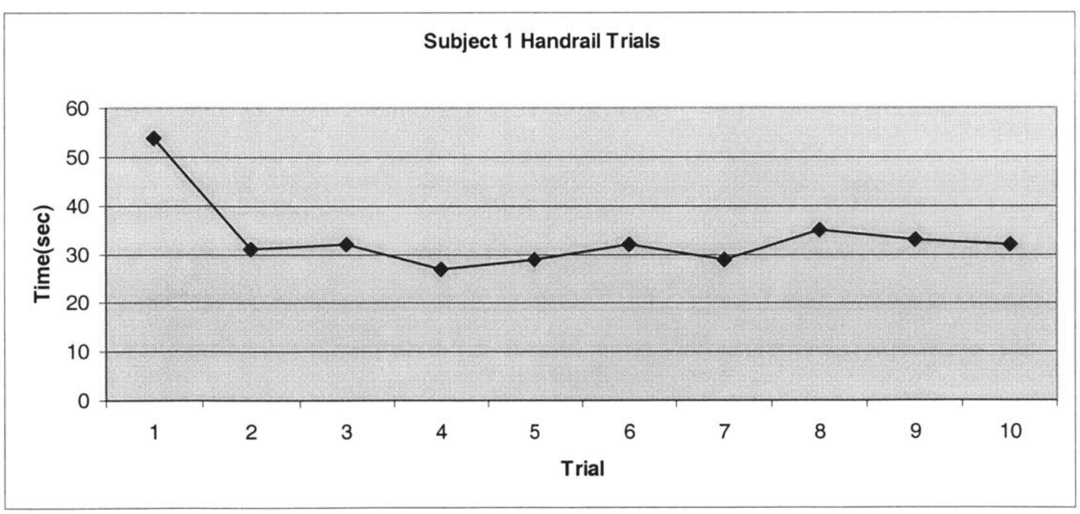


Figure K.6 Subject 1 handrail trials task time

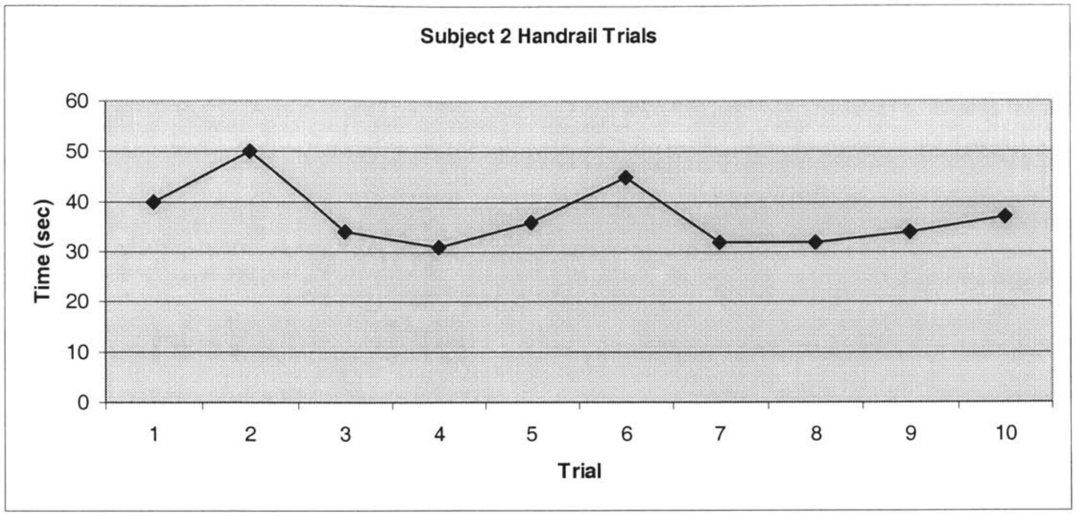


Figure K.7 Subject 2 handrail trials task time

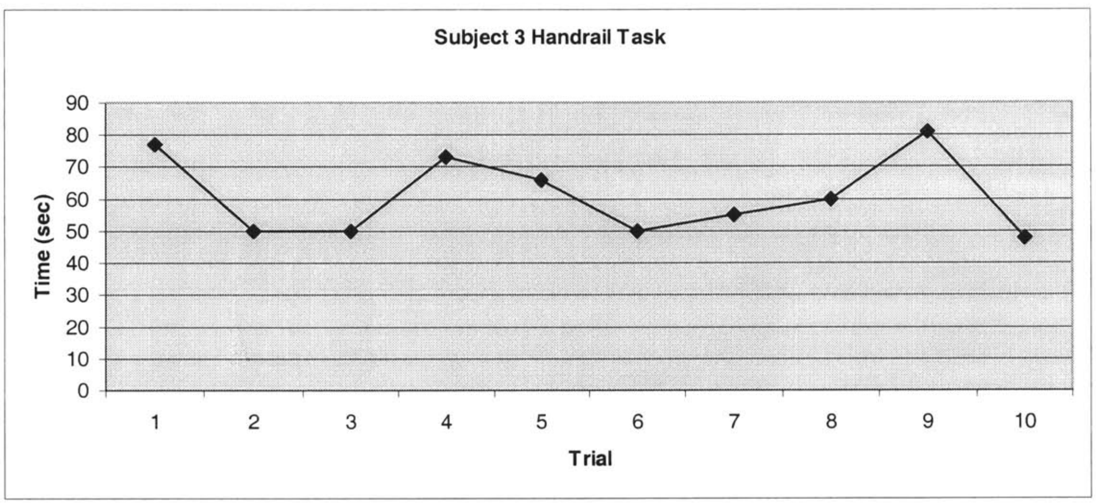


Figure K.8 Subject 3 handrail trials task time

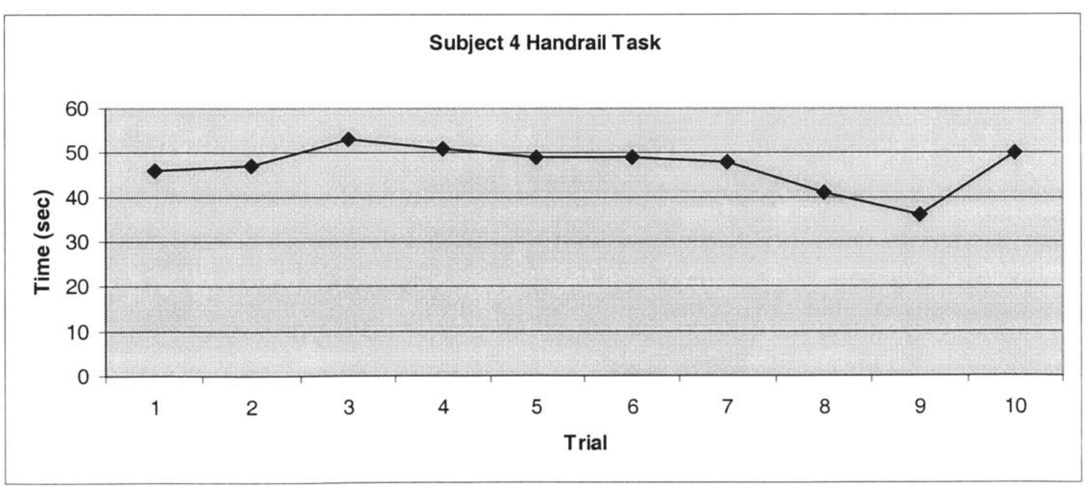


Figure K.9 Subject 4 handrail trials task time

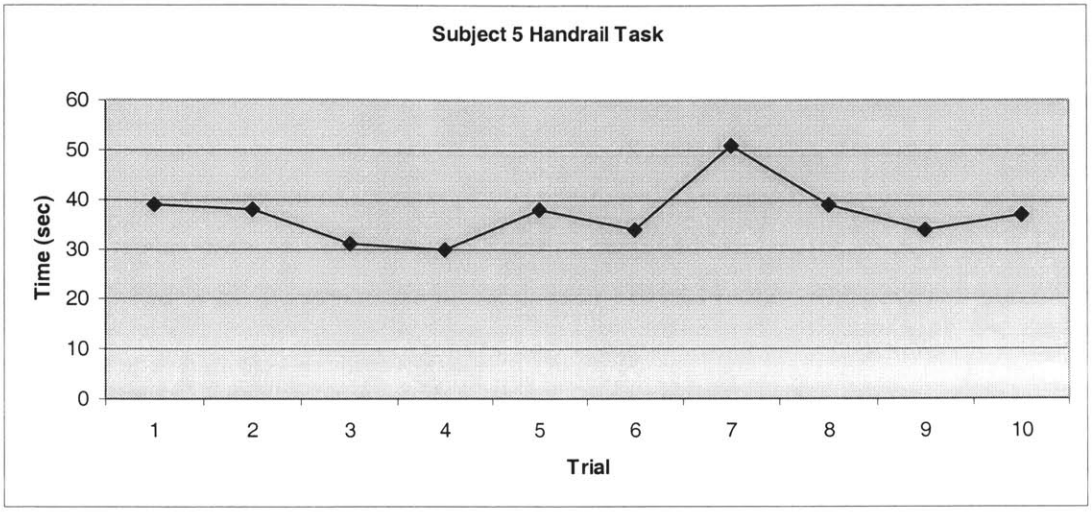


Figure K.10 Subject 5 handrail trials task time

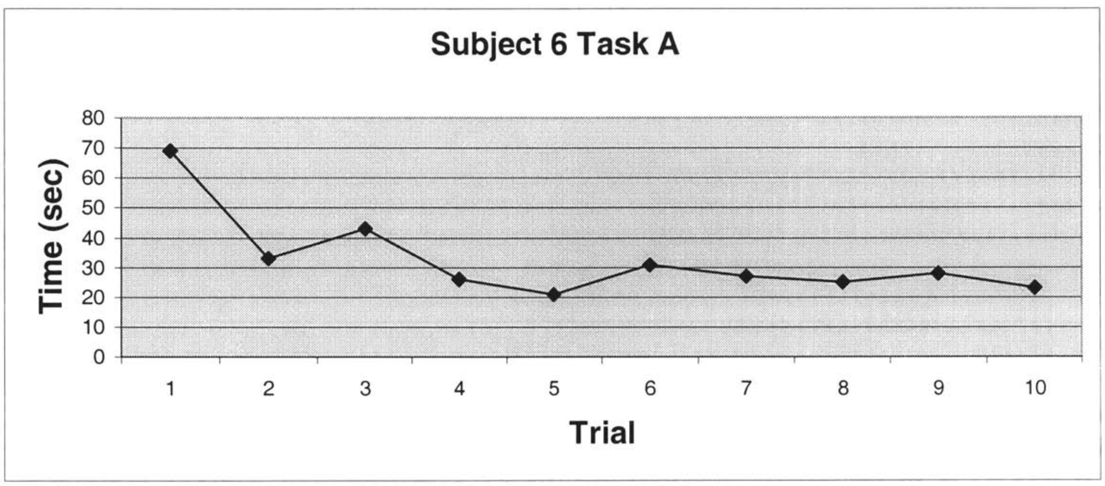


Figure K.11 Subject 6 handrail trials task time

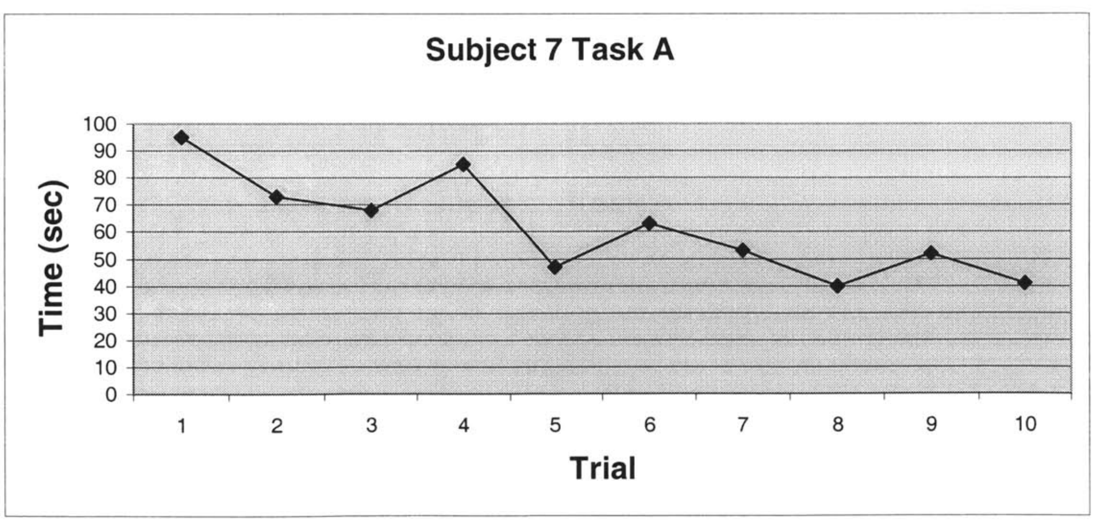


Figure K.12 Subject 7 handrail trials task time

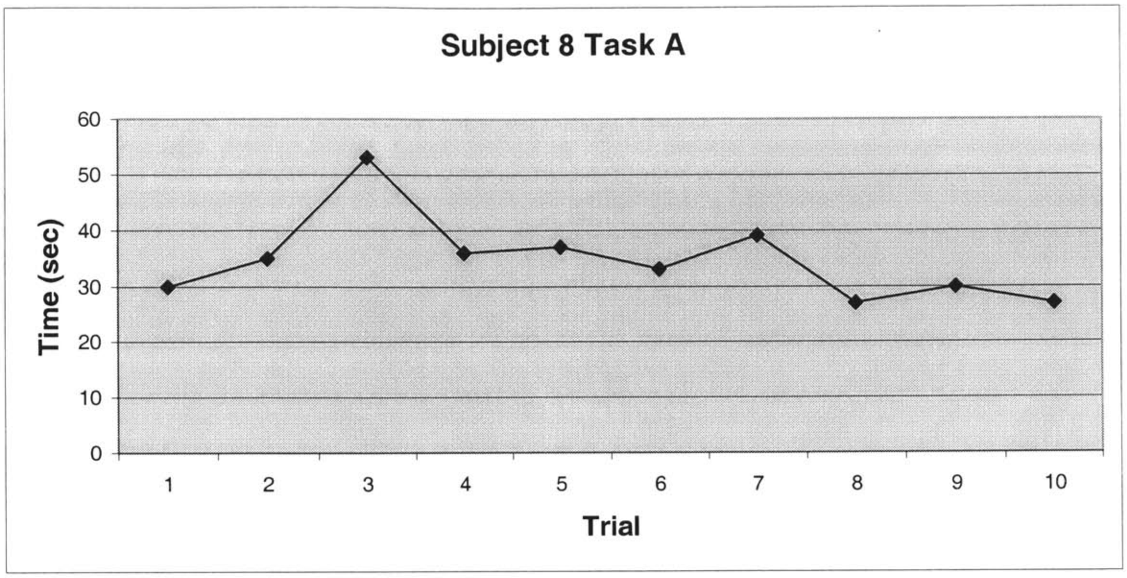


Figure K.13 Subject 8 handrail trials task time

Figures K.14 through K.21 show the drill task times for each subject

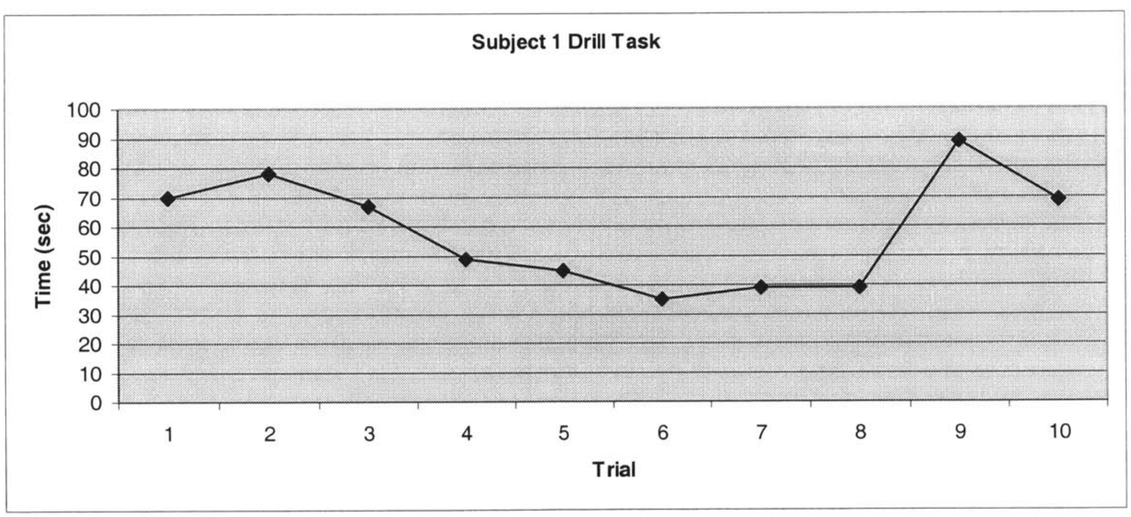


Figure K.14 Subject 1 Drill task times

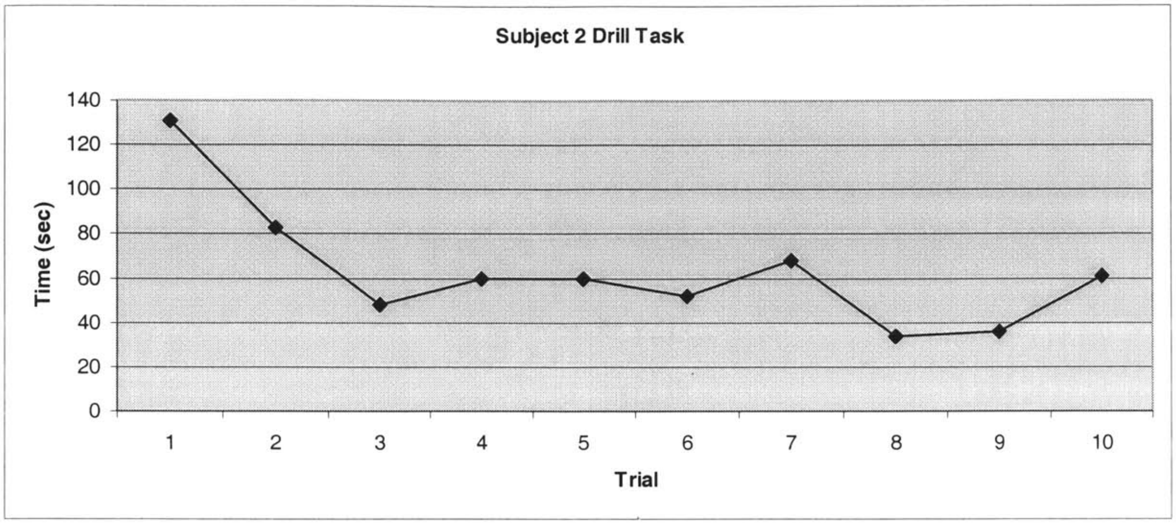


Figure K.15 Subject 2 handrail trials task time

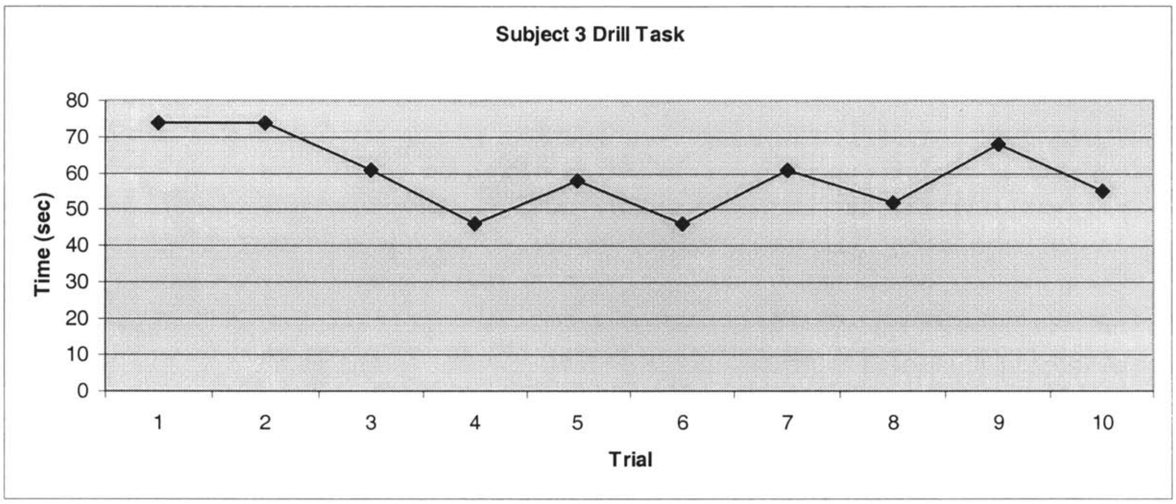


Figure K.13 Subject 3 handrail trials task time

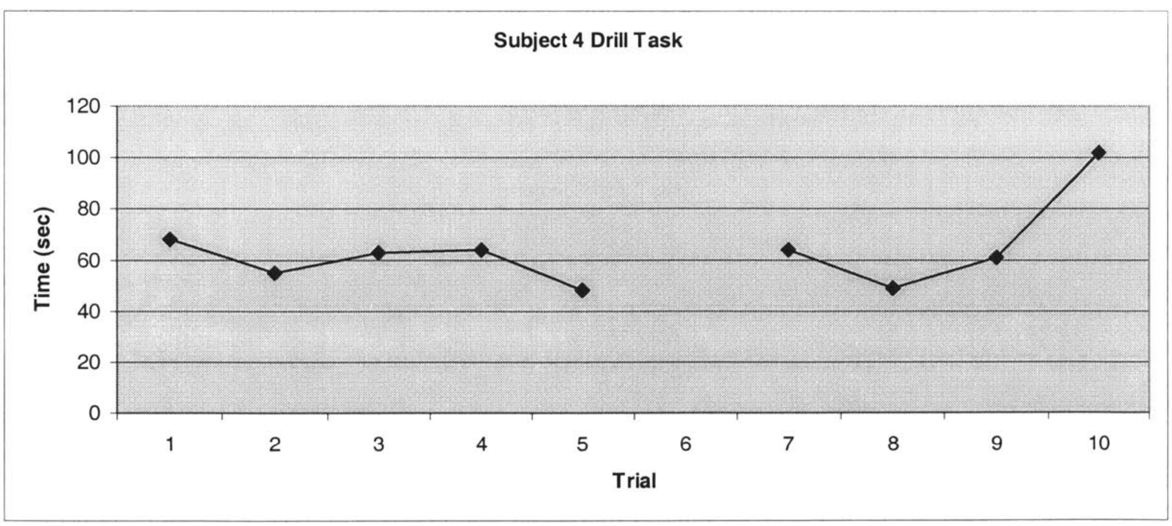


Figure K.17 Subject 4 handrail trials task time

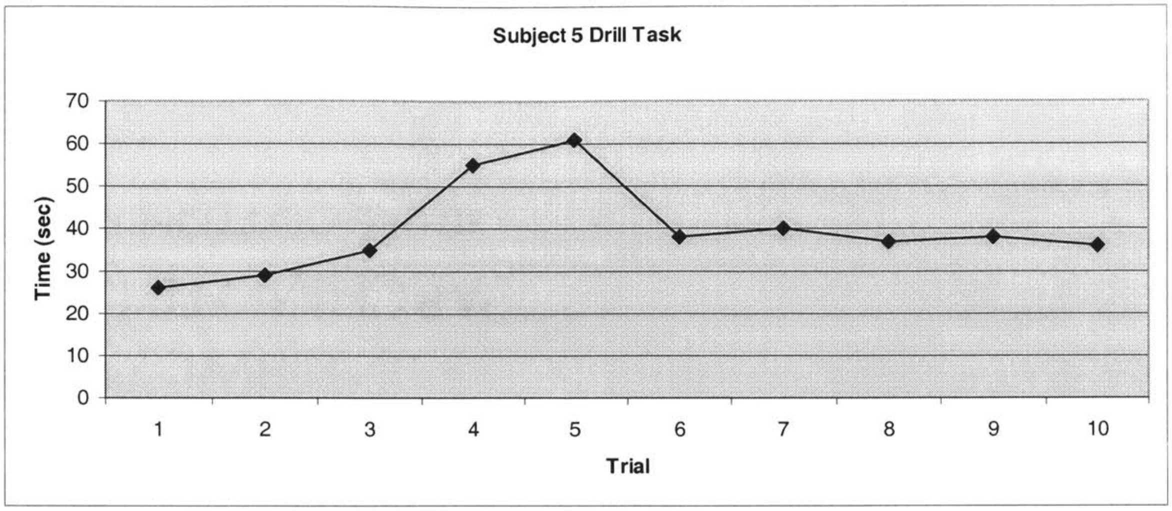


Figure K.18 Subject 5 handrail trials task time

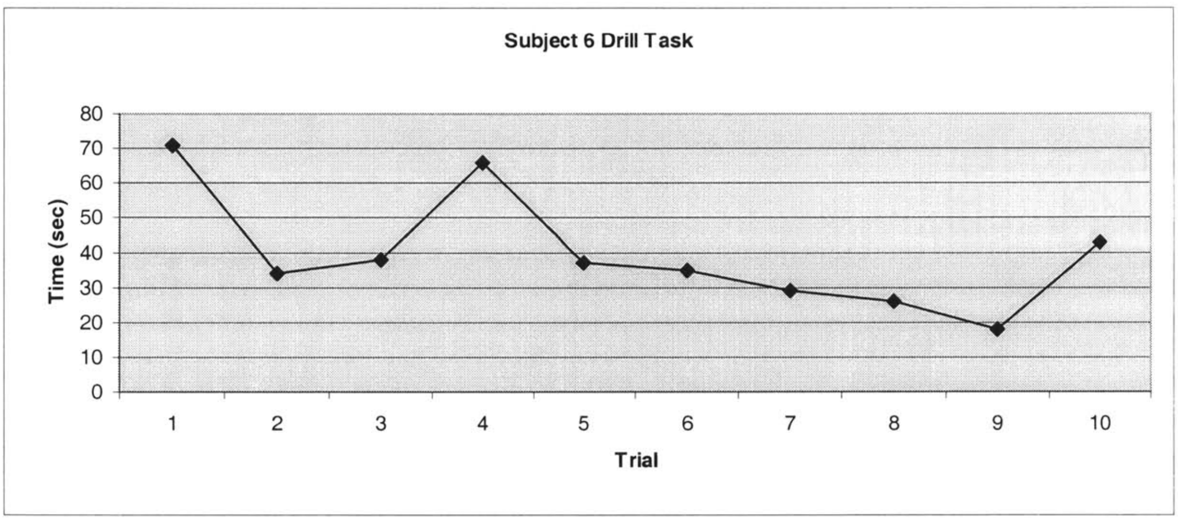


Figure K.19 Subject 6 handrail trials task time

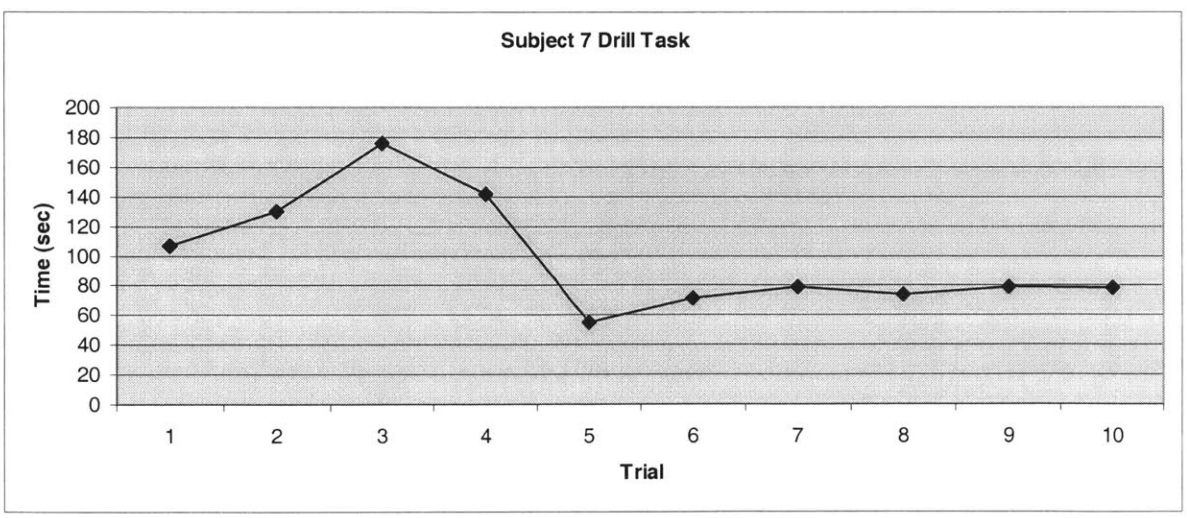


Figure K.20 Subject 7 handrail trials task time

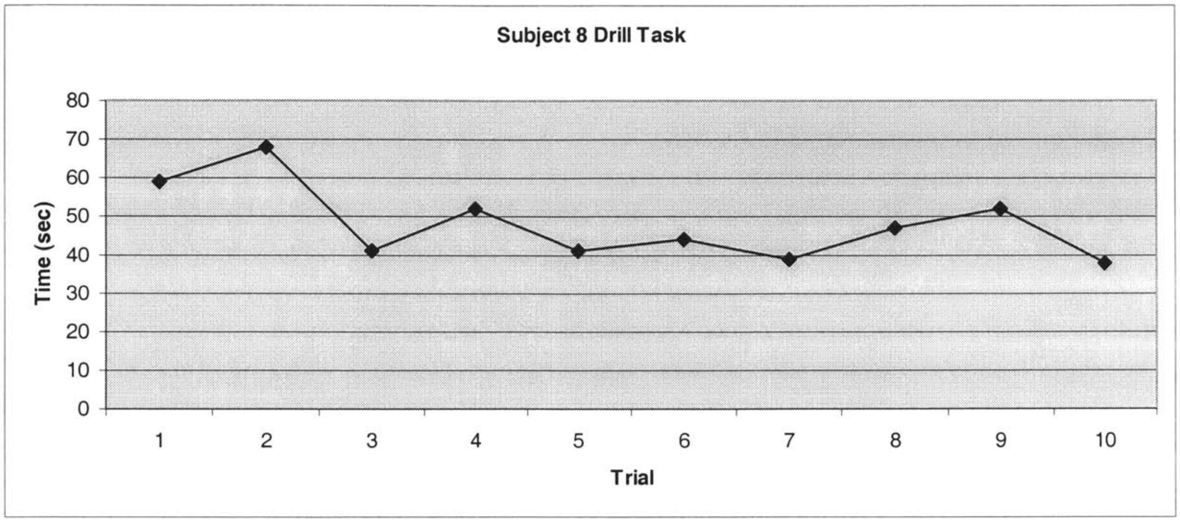


Figure K.21 Subject 8 handrail trials task time

Appendix L Basis and Integrated Subjective Questionnaire Responses

The following appendix lists the subjective questions asked of the subject after each trial. In most cases, the answers for each of the basis task modes (manual, simulated and robotic) are shown adjacent to one another for comparison. As there were some questions that were unique to a particular modality, the other modality responses are left blank.

L.1 Basis Task Questionnaire Responses

L.1.1 Section 1

1) Did you experience any fatigue during the trials? If so, where (on body, or mental) and at what point during the test did this occur?

Subject	Manual	Simulated	Robotic
1	Some Fatigue – slight head/neck ache developed progressively during test	Some Fatigue – slight arm	Some Fatigue – some arm
2	Some Fatigue – hand and eyes, towards the end of the test	Some Fatigue – back (upper), shoulder – right, fingers, wrist and neck	Some Fatigue – wrist and neck
3	No Fatigue	Some Fatigue – forearm, wrist, neck – occurred towards the end	Major Fatigue – arm towards the end
4	Some Fatigue – minor on head and arm	Some Fatigue – some mental towards the end – tired from concentrating	Some Fatigue – at midpoint, my arm was a little tired, but after a short break, it was fine. Some overall fatigue towards the end

5	No Fatigue	Some Fatigue – eye strain half way through the exercise	Some Fatigue – shoulder, wrist about ¼ way into test sequence
6	No Fatigue	Some Fatigue – shoulder joint fatigue	No Fatigue
7	Some Fatigue – physical, deltoid on push panel (last five minutes). Mental, losing focus	No Fatigue - Less fatigue than 1st test – more movement, less isolation on joints	Some Fatigue – upper arm went 1st – mental focus was lost quickly after that. After 1st several tasks is when fatigue wore in
8	Some Fatigue – concentration only in the last few runs	Some Fatigue – mostly body (arm/shoulder)	Some Fatigue – some arm and some brain – but mostly it was fun

2) What methods did you use to combat fatigue during the trials?

Subject	**Manual**	**Simulated**	**Robotic**
1	None – closed eyes between tests	Rested on my side	Was ok once I rested my arm on my side
2	Loosened hand, blinked eyes	Moved shoulder and wrist	Loosened my wrist, neck rolls
3		I tried to rest my arm and relax my wrist	I help up my right arm with my left arm in between trials. That helped a lot!
4	Resting arm on leg	Closed my eyes	Kept my elbow close to my body
5		Closed eyes during rest periods	Freeze/thaw
6		Held my left fist under my right elbow	No Fatigue
7	Counting		Refocus
8	Attempt to stay focused only when necessary	Resting arm as soon and often as possible	Well adjusted transform to begin with – frequent arm resting

3) Did you experience any physical discomfort during the trials? If so, please describe:

Subject	Manual	Simulated	Robotic
1	See previous	Some – top of helmet "digging" into top of head slightly	No
2	No	Yes – upper back and shoulders started to hurt halfway through the experiment	No
3	No	Yes. My helmet was too tight. My wrist was being twisted into uncomfortable positions for long periods	Yes. My helmet was too tight
4	No	No	No
5	No	Yes. Some wrist discomfort while trying to control sim robot wrist	Yes. Shoulder fatigue. Seat was uncomfortable
6	Yes, at the rear of my neck – top of my back	Yes. Very mild motion sickness	No
7	Weight of helmet	Yes. Slight pressure point on head	None besides fatigue
8	Not much – had to hold my head very still to prevent helmet from slipping (glasses)	Minor arm fatigue	Yes. Minor arm fatigue

L.1.2 Task Specific Questions

1) Please rate the overall difficulty of the **TAPPING** task, 1 being Very Easy and 5 being Very Difficult

Subject	Manual	Simulated	Robotic
1	1	3	4
2	1	4	1
3	2	4	3
4	2	2	2
5	1	4	3

6	1	3	2
7	2	3	2
8	1	4	3

2) Please elaborate on the level of difficulty:
____The entire task was easy
____A few parts of the task were difficult, but most of the parts were easy
____Half of the task was easy, half difficult
____Most of the task was difficult, only a few parts were easy
____The entire task was difficult

Subject	**Manual**	**Simulated**	**Robotic**
1	The entire task was easy	A few parts of the task were difficult, but most of the parts were easy	Most of the task was difficult, only a few parts were easy
2	The entire task was easy	Half of the task was easy, half difficult	The entire task was easy
3	A few parts of the task were difficult, but most of the parts were easy	Most of the task was difficult, only a few parts were easy	Half of the task was easy, half difficult
4	A few parts of the task were difficult, but most of the parts were easy	A few parts of the task were difficult, but most of the parts were easy	A few parts of the task were difficult, but most of the parts were easy
5	The entire task was easy	Half of the task was easy, half difficult	A few parts of the task were difficult, but most of the parts were easy
6	The entire task was easy	Half of the task was easy, half difficult	A few parts of the task were difficult, but most of the parts were easy
7	A few parts of the task were difficult, but most of the parts were easy	Half of the task was easy, half difficult	A few parts of the task were difficult, but most of the parts were easy
8	The entire task was easy	Most of the task was difficult, only a few parts were easy	A few parts of the task were difficult, but most of the parts were easy

3) Which sections of the task did you find difficult and why?

Subject	Manual	Simulated	Robotic
1	N/A	Depth perception – knowing how close I was to the board – maintaining slower speed	Moving horizontally seemed more difficult than moving vertically
2	Tapping purple squares. They were further apart. Depth perception was harder to recognize	Outer squares more difficult particularly left ones	None
3	Tapping to purple squares. I had to keep moving my head to see	It was very difficult when I first started. Depth perception was a major problem. I had no idea where I was relative to the board, from a distance perspective	At the beginning it was difficult but I had much more depth perception
4	The purple color seemed the more difficult task because it was at the edge of the field of view. Yellow had the same reach as purple, but did not require any head movement b/c of wider FOV	The points farther away from the target were harder to touch. Depth perception was not as clear further out	The most distant points were the most difficult. There was more work involved in keeping the hand at a constant distance above the board when going from point to point
5	Outermost squares were just outside the field of view of the HMD. Had to turn head, acquire square then touch square	Making contact with the squares. Fine positioning was difficult to control	Fine positioning tasks
6		Not knowing how far I was away from the board because I could not resolve the 3-D nor did I have my sense of feel. Keeping my "off" fingers out of	Determining how far away from the board was a little difficult but between the shadows

		the board because I could not articulate my index finger	
7	Limited vertical FOV for tapping purple. Red and green are tedious because of proximity	Depth perception of board – keeping hand on right side. Vertical tapping seemed much harder than horizontal tapping	Close dots – added to upper arm fatigue
8	Far apart dots outside FOV	Long transversals required much concentration to coordinate head and arm motion	I found the lag hard to compensate for as I went faster

4) Which sections of the task did you find easy, and why?

Subject	**Manual**	**Simulated**	**Robotic**
1	All – easy to see, easy to move arm	Seeing squares, seeing movement, performing movement	
2	Tapping the red and green – they were closer	Tapping green or orange – they were closer	All of it
3	The red and green squares. They're close together and easy to see	None	It was easier to locate where I was on the board
4	All of the close in colors	Points closer to center – better dexterity	The points close to the center were easier. Most of that task was targeting, not straight-line motion
5	Closer squares were easier since right/left, top/bottom pairs were within HMDs FOV. Could pan/slew eyes to acquire target instead of moving head	Translating from one square to the next. Rough/coarse positioning was easier to do	Coarse positioning. Making long sweeping motions

6	Generally all of the task was easy because pointing and touching are tasks that I am familiar with	Positioning the hand because it was "natural"	Overall the task was easy. Although it was slower, it was easier than the manual section because Robonaut could be indexed so my elbow was at rest
7	Middle distance colors – required no head movement and moving more than just wrist	Closer proximity tapping	Far points – more motion
8	Close dot pointing – both dots easily within FOV	Short horizontal transversals allowed only minor pose changes in my arm	Sensing 2-depth was surprisingly easy

5) Did you find that the more times you did the task that it's level of difficulty (circle one):

Subject	**Manual**	**Simulated**	**Robotic**
1	Remained the Same	Decreased	Decreased - slightly
2	Decreased	Decreased	Decreased
3	Decreased	Decreased	Decreased
4	Remained the Same	Decreased	Remained the Same
5	Decreased	Remained the Same	Remained the Same
6	Remained the Same	Decreased	Decreased
7	Decreased	Decreased	Remained the Same
8	Decreased	Decreased	Decreased

6) Please explain the above response:

Subject	**Manual**	**Simulated**	**Robotic**
1	Thought I did "well" every time, wasn't hard	Seemed to get used to the way the arm/hand moved and got used to speed	I became familiar with how the robot would react to movements
2	I became more familiar with the location/orientation of the squares on the board	When I moved closer to my body I had better control	Repetitiveness helped
3	I could tell I was getting better as I	Towards the end I had a much better	I had a much better idea of the robot's

	went. I was much more comfortable as time went on	idea of where I should be. Controlling the "robot" hand became easier	capabilities and my interface with the robot
4	There did not seem to be a learning curve i.e. straight-forward task	I was able to judge the depth better	The task was fairly simple to perform from the beginning
5	Got used to location of squares and relative movement of arm to get to appropriate square	Positioning the sim finger accurately remained a difficult task	Spent most of my time concentrating on control of accurate positioning
6	It was simple enough that it had very little learning curve and there was a little fatigue involved so it never became physically more difficult	Basically because I became increasingly familiar with what motions created what results	The task became easier as I learned the motion of the wrist
7	Got accustomed to FOV for tapping purple	Accommodation to reaction time and motion of the "hand"	Got accustomed to arm behavior but fatigue was hard
8	At first the task became easier because I learned to anticipate trajectory (of my hand) corrections. Towards the end, fatigue slowed me slightly	I learned to anticipate the lag of the virtual arm	Over time I could better compensate for lag

7) Did you alter your strategy during the tapping task at all during the course of the experiment? Please explain:

Subject	Manual	Simulated	Robotic
1	No	A little – tried not to punch so much through board	No
2	Yes. Moved head up/down left/right rather than sit still	Yes – I lifted my arm more towards my body – rotated wrist a little	No

3	Yes. I tried to focus more on the lower green, blue and purple squares (when I was doing each set). I found that I could reach the upper squares easily, but the lower ones took much more focus and concentration	Yes. I put more thought into what the "robot" was doing as opposed to what my arm was doing	Yes. I tried to get as close as possible to the board
4	No	No	No. I was fairly consistent with my approach
5	Yes. With the yellow and purple squares I tried to fit left and right squares within outer boundary of HMDs FOV. This way I could pan eyes and acquire target without (or as little as possible) moving my head	No	Yes. Looked for deflection in the task board as a cue for contact
6	Yes. During the purple touching, I attempted not to move my head to see both purple squares. The purple squares could barely be kept in the field of view at the same time	Yes. I used my wrist more during the latter part of the test	No
7	No	Yes. At 1st no strategy taken. Eventually started trying to remember position of arm to tap buttons. Also started to wait for hand and to predict residual motion	No

8	Yes. I found that it was helpful to maximize my FOV so I kept my head back more	Yes. I tried to keep my v-hand in the FOV more – more coordination between head and arm	Yes. I tried to remain closer to the board to reduce the total trajectory distance

8) Please rate the overall difficulty of the **TRACING** task, 1 being Very Easy and 5 being Very Difficult (circle one)

Subject	**Manual**	**Simulated**	**Robotic**
1	1	3	
2	1	4	2
3	2	5	4
4	2	3	2
5	2	4	3
6	1	3	2
7	2	3	3
8	2	3	4

9) Please elaborate on the level of difficulty:

____The entire task was easy
____A few parts of the task were difficult, but most of the parts were easy
____Half of the task was easy, half difficult
____Most of the task was difficult, only a few parts were easy
____The entire task was difficult

Subject	**Manual**	**Simulated**	**Robotic**
1	The entire task was easy	A few parts of the task were difficult, but most of the parts were easy	Most of the task was difficult, only a few parts were easy
2	The entire task was easy	Most of the task was difficult, only a few parts were easy	A few parts of the task were difficult, but most of the parts were easy
3	A few parts of the task were difficult, but most of the parts were easy	Most of the task was difficult, only a few parts were easy	Half of the task was easy, half difficult
4	The entire task was easy	Half of the task was easy, half difficult	A few parts of the task were difficult, but most of the parts were easy
5	A few parts of the task were difficult, but most of the parts were easy	Most of the task was difficult, only a few parts were easy	Half of the task was easy, half difficult

6	The entire task was easy	Half of the task was easy, half difficult	A few parts of the task were difficult, but most of the parts were easy
7	The entire task was easy	Half of the task was easy, half difficult	Half of the task was easy, half difficult
8	A few parts of the task were difficult, but most of the parts were easy	Half of the task was easy, half difficult	Half of the task was easy, half difficult

10) Which sections of the task did you find difficult and why?

Subject	**Manual**	**Simulated**	**Robotic**
1	N/A	Maintaining constant distance from the board	Keeping close on the board – moving in a straight line (horizontal harder)
2		Tracing was difficult particularly green and yellow	Tracing backwards/CCW was a little difficult because I was having to reach across (from the left)
3	Tracing the outer square was more difficult. I kept going outside the lines. Also transitioning from the diagonals to the square was a little difficult	Depth perception was incredibly difficult. I kept going into the board. Following a straight line was difficult	Following a straight line was difficult. Especially when I had to extend my arm
4	The task was fairly easy. It was mainly remember the sequence for the 'x' at the beginning	The 'x' was more difficult as well as the bottom section of the square – just seemed harder to coordinate	The sections where I was moving the hand towards the robot body seemed more difficult – harder to reach in front vs. to the right
5	Counter clockwise trace. Remembering the order of the tracing pattern	Maintaining contact with the appropriate line	Maintaining contact with the lines
6		Similar to tapping,	Same as tapping,

		difficult to determine how far I am away from the board because of the 3-D factor and feel. Also keeping my "off" fingers out of the board	determining distance from the board was difficult
7	Clockwise – forgot to do cross stripes on occasion	Moving from corner point (i.e. coming off of board to relocate for cross lines)	Felt scaling of motion was off - more "real motion" to attain proper robot motion
8	Unfortunately it took a while to learn CCW	I found it difficult to quickly get to a new line	I found it difficult to maintain a constant distance from the board

11) Which sections of the task did you find easy, and why?

Subject	**Manual**	**Simulated**	**Robotic**
1	All - easy to see and move arm	Seeing lines	
2		Tracing red line was easy	Tracing CW – I'm accustomed to drawing a box and an 'x' in these directions
3	The diagonals were easy. I didn't have to move my head or my eyes very much	None	Locating the corners was much easier than it had been
4	The [outer] square	Tracing the top section of the square	Re – top part of the square in CW direction. Purple also seemed fairly easy
5	Clockwise trace. Right to left, top to bottom pattern was easier for me to remember (might be a righty thing!)	Nothing easy about this task	Large sweeping motions. Translating from resting position to starting position
6	All of the task because moving my finger across a surface in a straight	Movement of the hand because it was natural	All portions were easy, just slow

	line is familiar to me		
7	Counter clockwise – getting the cross stripes out of the way	Tracking cross lines seemed easier than orthogonal lines – no clue why	Fatigue was less than for tapping dots
8	CW – possibly due to my right handedness	Continuous transversals were easier because they remained near the center of the FOV	Maintaining a straight line (in x-y plane) wasn't too hard

12) Did you find that the more times you did the task that it's level of difficulty (circle one)

Increased Remained the Same Decreased

Subject	Manual	Simulated	Robotic
1	Remained the Same	Decreased	Decreased
2		Decreased	Decreased
3	Decreased	Decreased	Decreased
4	Decreased	Decreased	Remained the Same
5	Decreased	Remained the Same	Remained the Same
6	Remained the Same	Decreased	Decreased
7	Decreased	Decreased	Decreased
8	Decreased	Decreased	Decreased

Please explain the above response:

Subject	Manual	Simulated	Robotic
1	Thought the whole thing was easy so no room for improvement		Same as before
2		Tracing – I concentrated more	I slowed down a little and the repetitions made it easier
3	Although it didn't decrease very much	I became more familiar with my surrounding	I had a better understanding of the robot's capabilities
4	It became easier as the sequence was learned	Was able to move along the lines faster	Each time I did the task I expected to be a little faster, but it always seemed to take the same amount of time to perform the task
5	Got used to the	Difficult to position	Placement

	pattern of the trace	finger accurately	positioning tool a lot of concentration
6	Very little learning curve, low fatigue	As I learned the sim's reactions to my movements, I compensated accordingly	As I learned the wrist motion, the task became easier
7	Vision adaption to limited FOV	Accommodation to behavior of hardware	Accustomization
8	My arm seemed to trace instinctively with less thought required	I better learned the ration of real arm motion to virtual. Also, tried to remain more conscious of my real arm's trajectory	My mental transform from real arm to robot arm improved over time

13) Did you alter your strategy during the tracing task at all during the course of the experiment? Please explain:

Subject	**Manual**	**Simulated**	**Robotic**
1	No	A little – tried to not go through the board and didn't as much about distance	No
2		Yes. I not only slowed down my movements I had to picture the square in my mind in order to control my hand and arm movements	Yes. I slowed down my movements when I was tracing CCW
3	Yes. I had to focus more in the turns while tracing the square. These transitions were also difficult	Yes. I again, became more aware of what the robot was actually doing	Yes. I tried to move faster and turn the corners more efficiently
4	No	Yes. Tried to move faster for smoother line	No. I considered different hand positions for reaching the corners, but the position I started with always seemed to work

5	Yes. Tried to keep head steady. When I moved my head I would have to steady the HMD first, then acquire the desired edge then move my finger to that edge	No	Yes. I looked for deflection in the task board as a cue for contact
6	No	No	No
7	No		No
8	Slightly. I tried to trace more precisely once transversal of the course was automatic	Yes	Not consciously

L.1.3 Polhemus Questions

1) Did the Polhemus trackers track your movements adequately:

Not At All   Some of the time   Half the time   Most of the time   Always

Subject	Simulated
1	Most of the time
2	Half the time
3	Most of the time
4	Always
5	Most of the time
6	
7	
8	Most of the time

2) Did the above answer depend on the speed at which you were moving:

____Tracked the same no matter what speed I moved
____Tracked better when I moved more slowly
____Tracked better when I moved more quickly

Subject	Simulated
1	Tracked the same no matter what speed I moved
2	Tracked better when I moved more slowly
3	Tracked better when I moved more slowly
4	Tracked the same no matter what speed I moved
5	Tracked better when I moved more slowly
6	
7	
8	Tracked the same no matter what speed I moved

3) Did the ability of the Polhemus to track depend on the movements you were doing?

If so, describe the types of movements (straight line, curved, planar, etc.) that caused it to:

Track Well:

Subject	Simulated
1	Seemed to track same
2	Moving from left to right slowly
3	It tracked well most of the time
4	It seemed to track well for all movements. The only thing I noticed was a slower update for faster moves i.e. view looked somewhat jerky
5	Slow motions, straight lines
6	
7	
8	Seemed consistent – but lag became more obvious at higher speeds

Track Poorly:

Subject	Simulated
1	Reached some kind of limit on left side and couldn't move anymore
2	When I was tracing counterclockwise, it did not track well when I was moving down the left side (green)
3	
4	
5	Fast motions only
6	
7	
8	

L.1.4 Additional Comments

1) Please comment on any hardware problems that may have been experienced during the trials:

Subject	Manual	Simulated	Robotic
1	N/A		None
2		None that I could tell	None
3	None	None	None
4	None	Length of glove cable – it snagged a couple of times, so I held the cable in my	None

		free hand	
5	Lack of field of view	Control of sim robot wrist was difficult	Indexing. Wrist control was difficult due to awkward position of my wrist relative to robot's
6	Through about 50% of the session the eye pieces were too far from the bridge of my nose and "flapped" around	None	None
7	N/A	Left eye view vs right eye view. Probably could have been adjusted but didn't realize until the task started	Forgot on occasion to control head movements was afraid of damaging robot head
8	Helmet slippage	I would lose fusion when the hand got close to my face	If you drive the arm quickly and decelerate quickly, the control will sometimes glitch – causes brief but high accelerations

2) Please comment on any software problems that may have been experienced during the trials:

Subject	Manual	Simulated	Robotic
1			None
2		None	None
3		None	None
4		Window moved – needed adjustment	None
5		None	None
6		None	None
7		None	Scaling range of arms
8		None	See previous

3) Do you feel that you had all of the information that you needed to complete the task?

Subject	Manual	Simulated	Robotic
1	Yes	Yes	Yes
2		Yes	Yes
3	Yes	Yes	Yes
4	Yes	Yes	Yes

5	Yes	Yes	Force info would have been nice
6	Yes	Yes	Yes
7	Yes	In 1st task the board was slanted – didn't know if board was slanted in the sim	Yes
8	Yes	I was not certain whether z-depth was as important as x-y accuracy	Yes

4) Do you think a display would have helped complete the tasks?

Subject	Manual	Simulated	Robotic
1	No	Maybe	No
2		Maybe	No
3	Yes	Yes	Yes
4	No	Yes	
5	No	Yes	Probably
6	No	No	No
7			No
8		Yes	

If so, please describe what information you would have liked in order to complete the task:

Subject	Manual	Simulated	Robotic
1		Distance to object/board	An indication of how close I was to the board
2		A display that could show me if I was getting too close to the board. A display that could show me if my elbow was up too high – my arm started to get tired because my elbow was up too high and needed to re-index very often	
3	Perhaps a display that showed more clearly the path I should take	An idea of my distance from the board would have been very helpful	

4		Display or overlay to indicate depth or proximity to target	A force display may have been helpful, but I think that I was fully occupied when performing the task and may not have had time to look at a display
5		Force/contact information	Force data. Arm orientation data
6			
7			
8	Virtual dots if outside the helmet and highlighted path/dots	A better z and Vz cue would have helped	

If not, why not?

Subject	Manual	Simulated	Robotic
1			
2			It was real time and I could see what I was doing
3			
4	Straight forward task		
5	Would have distracted me from moving to the target. Needed full attention on visual contact with target objective	The task was easily committed to memory	
6	It was a simple task that could easily be committed to memory	Being small brained, just completing task was consuming enough. Extra displays would take additional processing especially in timed processes	The task was easily remembered
7	Not necessary		Again, too much info is a bad thing
8			Z and dz/dt may have helped, but

			only minorly

5) Please comment on any aspect of the experiment that you wish to elaborate on, suggestions you may have, or comments:

Subject	**Manual**	**Simulated**	**Robotic**
1	I had to move my head to do the purple tapping because smaller vertical field of view – rest [of the] squares required no head movement		Seemed like there was a displacement between what my vision viewpoint was and what it should be. What looked "horizontal or vertical" required a diagonal hand movement – was/felt a little unnatural
2	Recognizing the depth perception took a minute or two. The white background bothered my eyes	Lack of depth perception made it difficult	
3	The only issue that I noticed was the colored squares and tracing board sometimes had rough sections where the tape had come off. I think sometimes (as I was tracing especially) this may have unnecessarily slowed me down	This was a lot more difficult than I thought it would be. But I think I improved after some experience	This section was much easier than the simulation. I felt I had much better control over the robot
4	Minor note – my legs were moved to the side to reach the lower sections	Overall it was hard to judge the depth of the target	I definitely preferred the robotic portion of the task versus the virtual. With the virtual, it was much harder to see the depth. As well, I had to move my head a lot more to see all of the

			targets/displays. With the video from the robot, I could see the whole task therefore I didn't move my head very much. Also, the depth was easier to see from the slight shadows on the display board. One thing with the video pan/tilt from the robot: it seemed a little disorienting when I did move my head compared to the virtual. Maybe it was a little faster than I expected.
5	Better display, i.e. more field of view	Eye fatigue was a problem	Wrist control was difficult. Elbow motion due to wrist roll was a bit tricky to get used to
6	I would have liked "buttons" for the colored squares so there would have been a positive pass/fail criteria when I touched the square	Positive feedback (such as the panel turning red) when the hand touches the panel	Again, buttons with a positive feedback would be nice on the touch portion
7	If the test is to see how well subjects adapt to gear for accuracy, test subjects w/o helmet first and only tracking equipment for gloves. Cameras in helmet limit FOV	Subject preparation (self) should have been more through calibration of arm/hand position (not sure what to say)	Depth perception was much better w/real hardware than sim. But more pressure to control real hardware added to fatigue (i.e. avoiding singularities)
8			I think that the VR – real robot world has lots of visual texture

			cues that the artificial world lacks – making stereo fusion easier and more accurate – that's my guess

L.2 Integrated Robotic Task Questionnaire Responses

L.2.1 Fatigue Questions

1) Did you experience any fatigue during the trials? If so, where (on body, or mental) and at what point during the test did this occur?

Subject	Response
1	Some Fatigue – some arm when extended long
2	Some Fatigue – neck sitting in a fixed position
3	Some Fatigue – arm, wrist. Towards the end but I never felt that I had to rest
4	No Fatigue
5	Some Fatigue – eyes, wrist
6	No Fatigue
7	No Fatigue
8	Some Fatigue – mostly mental – I tended to get sloppy towards the end

2) What methods did you use to combat fatigue during the trials?

Subject	Response
1	Rest on side
2	Moved my head
3	I didn't need to use any
4	The indexing may have helped – change of body positions
5	
6	
7	
8	Keeping arms both in minimum torque position in between runs

3) Did you experience any physical discomfort during the trials? If so, please describe

Subject	Response
1	No

2	No
3	Yes. Wrist was twisting
4	No
5	No
6	No
7	No
8	Just fatigue

L.2.2 Task Specific Questions

1) Please rate the overall difficulty of the **DRILL** task, 1 being Very Easy and 5 being Very Difficult (circle one)

Very Difficult 5 4 3 2 1 Very Easy

Subject	Response
1	4
2	4
3	3
4	3^{+}
5	2
6	2
7	3
8	3

2) Please elaborate on the level of difficulty:

____The entire task was easy
____A few parts of the task were difficult, but most of the parts were easy
____Half of the task was easy, half difficult
____Most of the task was difficult, only a few parts were easy
____The entire task was difficult

Subject	Response
1	Most of the task was difficult, only a few parts were easy
2	Most of the task was difficult, only a few parts were easy
3	Half of the task was easy, half difficult
4	Half of the task was easy, half difficult
5	A few parts of the task were difficult, but most of the parts were easy
6	A few parts of the task were difficult, but most of the parts were easy
7	Half of the task was easy, half difficult
8	Most of the task was difficult, only a few parts were easy

3) Which sections of the task did you find difficult and why?

Subject	Response
1	Aligning peg in hole
2	Reaching for the drill without hitting it with the thumb. Aligning the drill without hitting the target and without too much force

3	Grabbing the frill was difficult, but I found that the robot didn't need a full grip to hold the drill. Putting the bit in the hole was sometimes difficult because I sometimes had trouble seeing
4	The grasping section could be difficult sometimes. With the camera view and the position of the fingers behind the drill, it was a little hard to tell if I had a good grasp. The insertion of the drill was a little difficult, but very doable at a slow pace.
5	Placing the drill into holder. Fine motion control was a bit tricky. Took a lot of concentration
6	Gripping the drill was difficult because I did not know if I had a good grip
7	Grasping – had trouble w/large drill grip. Started rushing after getting complacent w/handrail task. Insertion b/c of lack of re-indexing (pilot error). Attaining good alignment was hard
8	I had a hard time getting the fingers to unfurl adequately. I was also sometimes overly focused on finger position and would fail to pay attention to loads through the arm

4) Which sections of the task did you find easy, and why?

Subject	**Response**
1	Movement
2	Gripping- once hand was aligned around drill
3	Re-aligning the drill for the second part. I was amazed at how mobile the wrists and elbow were
4	Removing the tool from the socket was easy because of the compliance in the tool
5	Grasping; translating the drill from holder location to final location
6	Other subtasks were easy because they were familiar
7	
8	I found alignment pretty easy – it was easy to see (in 3-d) the necessary trajectory for mating

5) Did you find that the more times you did the task that it's level of difficulty (circle one) Increased Remained the Same Decreased

Subject	**Response**
1	Decreased
2	Decreased
3	Decreased
4	Decreased
5	Decreased
6	Decreased
7	Decreased
8	Remained the Same

6) Please explain the above response:

Subject	Response
1	I got used to knowing a good from a bad grasp and keeping my own hand from blocking my view
2	I got a better angle of the drill by moving my wrist
3	I learned the best way to approach the tasks. I definitely felt more comfortable as time went on
4	The more I performed the task the easier it became to see the cues that would tell me when I was grasped or seated on the socket. There were a couple of times when the indexing didn't feel quite right and so the motions weren't quite what I expected, but I felt better able to adapt to it the more times I performed the task
5	Grasping, I thought would be difficult. After the first few grasps it became quite easy
6	As I determined what a good reach was and when I got good cues for inserting the drill, the task got easier
7	Got more accustomed to pitch and yaw of wrist to align hole
8	I seemed to have less fatigue early on which helped offset the slight learning curve

7) Did you alter your strategy during the drill task at all during the course of the experiment? Please explain:

Subject	Response
1	No
2	Yes. Re-indexing!!! I paid closer attention to my wrist movement
3	Yes. I tried to get a better grasp on the drill from the beginning. I tried to remove it from the hole in a straight line (though I failed almost every time)
4	No. The strategy I used was the same throughout the experiment, but I became more adept at performing the task. When I was unsuccessful, I would pull away and try again
5	No
6	Yes. When grasping, concentrated on the thumb position. When inserting, progressively got more "Aggressive"
7	Yes. Didn't freeze – stay on last attempted. Felt more comfortable b/c I didn't have to readjust to a new position
8	Slightly. I tried to remain more aware of the hand/fingers as a whole so that I would lose awareness of contact forces

8) Please rate the overall difficulty of the **HANDRAIL** task, 1 being Very Easy and 5 being Very Difficult (circle one)

Very Difficult 5 4 3 2 1 Very Easy

Subject	Response
1	2

2	2
3	4
4	2^{+}
5	2
6	2
7	2
8	4

9) Please elaborate on the level of difficulty:
____The entire task was easy
____A few parts of the task were difficult, but most of the parts were easy
____Half of the task was easy, half difficult
____Most of the task was difficult, only a few parts were easy
____The entire task was difficult

Subject	**Response**
1	A few parts of the task were difficult, but most of the parts were easy
2	A few parts of the task were difficult, but most of the parts were easy
3	Half of the task was easy, half difficult
4	A few parts of the task were difficult, but most of the parts were easy
5	A few parts of the task were difficult, but most of the parts were easy
6	A few parts of the task were difficult, but most of the parts were easy
7	A few parts of the task were difficult, but most of the parts were easy
8	Half of the task was easy, half difficult

10) Which sections of the task did you find difficult and why?

Subject	**Response**
1	Getting a good grasp
2	Reaching under the handrail and trying to position the hand in the center
3	Getting my hand under the rail. I couldn't completely straighten my fingers
4	The most difficult part was inserting the fingers under the handrail. It was usually at an extended position and the fingers were curled a little. Pitching the hand down definitely helped
5	Placing the handrail on the hook. Lining up the handrail ring with the hook took a lot of wrist manipulation
6	Positioning the hand between the rail and handrail was somewhat difficult because of the lack of touch and depth perception
7	Opening hands enough and sliding under rail for grasping

8	Final approach on the rail was difficult – both in terms of reach and tight hand clearance

11) Which sections of the task did you find easy, and why?

Subject	Response
1	
2	Rotating the arm and hanging the handrail
3	Lifting and attaching the rail to the bungee. I could see very well!
4	Hooking the handrail was easy. Once the handrail was grasped and rolled to the vertical position, it was easy to maneuver. Also the end of the bungee cord was very easy to see in the camera video
5	Grasping the handrail and translating to the bungee hook
6	All of the sections were easy because they were familiar actions
7	
8	Latching the hook – few forces to worry about – stereo depth was pretty good

12) Did you find that the more times you did the task that it's level of difficulty (circle one)

Increased Remained the Same Decreased

Subject	Response
1	Decreased
2	Decreased
3	Decreased
4	Decreased
5	Decreased
6	Decreased
7	Decreased
8	Decreased

12a) Please explain the above response:

Subject	Response
1	I found that even when I thought was a "bad grasp position" worked ok, so were less precise in hand positioning
2	I got a better feel for where the hand/arm was position. I opened my hand more
3	I learned how to grab the drill and readjust it if I needed to
4	It was much easier to determine when to close the fingers the more times I performed the task. Also, when hooking the handrail on the bungee, at the beginning of the experiment, I was much more careful and precise about the hooking task. Whereas at the end of the experiment I felt more confident about hooking the handrail in different configurations

5	Again, grasping became an easy task and manipulating the (my) wrist for handrail/hook alignment became more intuitive with practice
6	As I became more familiar with \Robonaut's reach, the task became easier
7	Readjusted technique for placing handrail on bungee
8	I learned to maintain better wrist control – anticipated the trajectory

13) Did you alter your strategy during the tracing task at all during the course of the handrail experiment? Please explain:

Subject	**Response**
1	A little. I was less concerned with having a perfect grasp so I think I could do it faster
2	Yes. Opened my hand to keep from hitting my thumb against the handrail
3	Yes. I tried to use my wrist more instead of my fingers
4	Yes. In the beginning I was waiting until I could see the tips of the fingers emerge from under the rail before I grabbed it. Towards the end, I was using the wrist pitch to roll the handrail into the palm and then grab it
5	No
6	Yes. I began closing my fingers as I got them under the rail so to curl the rail with my fingers
7	Yes. Tried more alignment before placing handrail on hook
8	Yes. Wrist – as explained above

L.2.3 Display Comments

1) Please comment on the overall usefulness of the displays

Frontal view of Robonaut:

Subject	**Response**
1	Somewhat Useful
2	Very Useful
3	Very Useful
4	Very Useful
5	Very Useful
6	Very Useful
7	Somewhat Useful
8	Somewhat Useful

Close-up of wrist:

Subject	**Response**
1	Not at all Useful
2	Somewhat Useful

3	Somewhat Useful
4	Not at all Useful
5	Somewhat Useful
6	Not at all Useful
7	Not at all Useful
8	Somewhat Useful

Both Displays Simultaneously:

Subject	**Response**
1	Somewhat Useful
2	Somewhat Useful
3	Very Useful
4	Somewhat Useful
5	Somewhat Useful
6	Very Useful
7	Somewhat Useful
8	Somewhat Useful

Combination Robonaut and Voice:

Subject	**Response**
1	Somewhat Useful
2	Very Useful
3	
4	Somewhat Useful
5	Very Useful
6	Very Useful
7	Very Useful
8	Very Useful

2) When you had only the **outside view of Robonaut**, at what points in the experiment did you use the display?

Subject	**Response**
1	I used it mostly before and after each experiment to make sure things were ok, didn't use it much at all during
2	When I was reaching. I looked at my forearm action
3	When I needed to know where my arm was
4	I mainly used it for gross functions e.g. Moving from the first part of the drill task to the second part. It was also very useful for the indexing step
5	At the start of the experiment to check for potential collision between elbow and body
6	Only when I felt the elbow was too high or too far into the body
7	Only used outside view at first to ascertain position of arm to body. As tasks proceeded, become less dependent on view. Used view at ALL end of tasks

8	Only a couple of times when someone said my elbow was nearly contacting

2a) Did you ever ignore the display? At what points or for what tasks?

Subject	**Response**
1	Yes – mostly whole time during experiment stereo video seemed to work ok
2	Sometimes. Usually when I was rotating the forearm (after grasping the handrail)
3	Yes, when I was doing intricate wrist and finger movements – when I was grabbing the handrail
4	I ignored the display when I was focusing on the main portion of the task and performing fine motions e.g. Grabbing handrail, inserting it on bungee cord, grabbing drill, removing drill from socket, inserting drill in socket
5	Yes. Didn't rely on the display once the drill and handrail tasks started
6	When I was in close proximity doing small movements, I ignored the display
7	N/A
8	Most of the time I ignored it – I was more intent on the real view of the fingers

2b) What about the display did you find useful or useless?

Subject	**Response**
1	Arm position in relation to body was useful
2	I could see if my elbow was too far out
3	Seeing where my body was was useful – I missed this display when it was gone
4	Mostly the forearm and elbow positions. I didn't notice the position of the head or the wrist at all
5	Useful – elbow orientation relative to body. Useless – size of display was a little too large. I found it was getting in my way
6	The most useful part of the display was to determine the position of the elbow
7	Good to determine if arm was going to hit body but b/c tasks only involved 1 arm, the wrist remained in sight and in mind at all times
8	It sometimes helped but also sometimes got in the way forcing me to move my head

2c) What improvements can you suggest to such a display?

Subject	**Response**
1	A back view might be better so don't have to do mapping to yourself
2	

3	Perhaps changing the color or the color at certain parts. I found that sometimes I lost the hand in front of the body because they blended together
4	I liked it – maybe to save room on monitor, use only part of the body or display the arm only – assuming the operator will know the body is upright
5	Different placement in the viewing area perhaps. Shrink the overall size
6	Turn the body red when the elbow gets too close to a reach limit or another part of the body
7	This display would be very useful when both arms are in use, b/c it is hard to determine where arms are w/use of only camera views
8	I think it would be good to have it displayed as a translucent overlay.

3) When you had only the **wrist view**, at what points in the experiment did you use the display?

Subject	**Response**
1	I didn't use the wrist display
2	None
3	A lot during the handrail. When I was trying to get underneath the rail. I didn't use it very much with the drill
4	I didn't use it very much – really only during setup when I had a lot of wrist pitch or yaw. Also when yawing under the handrail
5	Did not use this display
6	Did not use the wrist view
7	N/A
8	On 2 rail runs I glanced at it – from then on I had learned how to tilt the wrist better without the display – guess It did help to train me early on

3a) Did you ever ignore the display? At what points or for what tasks?

Subject	**Response**
1	Yes – whole time
2	Yes – all motion occurring towards the right, I seldom looked up and to the left during the experiment
3	Yes – during the drill and once I had the handrail. I could see very well so I didn't need display
4	I ignored it during the grasping parts of the task
5	Always ignored. Actually I didn't need it. My view of the Robonaut wrist was good enough to perform all tasks
6	I always ignored the wrist
7	
8	During the last half of the session I no longer referred to the display

3b) What about the display did you find useful or useless?

Subject	Response
1	I could see my hand enough that I didn't need an additional display
2	None
3	It's presence – it was overall pretty good
4	Yaw/pitch was useful. Hand open/close – didn't really noticed – used camera view instead
5	Didn't rely on this display
6	N/A
7	
8	It only helped in the beginning

3c) What improvements can you suggest to such a display?

Subject	Response
1	Could be useful if robot hand obscured, then it would be nice to have orientation match
2	Leave it out
3	It was sometimes difficult to see the exact pitch of the wrist. Color was somewhat of a problem
4	No suggestions
5	
6	If it turned red to warn of a reach limit, then I would use the display
7	Again, since tasks were one arm only, the physical camera view was all that was necessary for wrist singularities
8	Maybe displaying the robot parts in their current perspective w.r.t. the user's FOV – less time to perform the transform mentally

4) When you had **both displays**, did you refer to:

One of them often___ Which one?_______ Both of them often______
One of them sometimes___ Which one?_______ Both of them sometimes_______
Neither of them___ Other_________________________________

Subject	Response
1	One of them sometimes - body
2	One of them sometimes - body
3	Both of them sometimes – it depended on the task
4	One of them sometimes - body
5	One of them sometimes - body
6	One of them sometimes - body
7	One of them sometimes - body
8	Both of them sometimes – early on

4a) Did you ever ignore the displays? Which one and at what points or for what tasks?

Subject	Response
1	Yes- during test, mostly ignored both
2	Yes – the wrist view – didn't use at all
3	Yes – outside view – during intricate wrist movements wrist view when I wasn't using my wrist excessively
4	Yes – during the grasping points of the task. In fact, there were times where the display was blocking my view and then I would adjust the camera view (re-center it)
5	Always ignored wrist. Used body only at task start to check for collision potential
6	I ignored both displays except for determining elbow position
7	Did not use close up of wrist
8	Yes, most of the time – especially after the first couple of runs

4b) What about the dual displays did you find useful or useless?

Subject	Response
1	Didn't really need either during task so dual useless
2	None
3	I could really tell the difference when I didn't have them. I felt I was missing quite a lot. At times I was concerned because I couldn't see what my arm and elbow were doing
4	Overall with two displays there was just a little too much to look at so I usually ended up ignoring both
5	Obstructed FOV
6	Indication of elbow position
7	Didn't use wrist close up
8	Never need both simultaneously

5) When you had the **single overlay with voice**, at what points during the task did you find the display:

Useful:

Subject	Response
1	When I was reaching I could see how my elbow/arm was
2	
3	
4	
5	Task start
6	Positional error indication was useful when manipulating the drill
7	Did not use overlays differently w/ or w/o voice
8	No change with voice- same as above

Useless:

Subject	Response
1	Whole time mostly
2	
3	
4	Didn't really use the overlay
5	When trying to grasp or place. Obstructed FOV
6	Comment concerning "gross" motions (go up, pull back, etc.) were annoying
7	
8	

6) When you had **no display**, did you find the task:

Easier Somewhat Easier No Different Somewhat Harder Harder

Subject	Response
1	No Different
2	Somewhat Harder
3	Somewhat Harder
4	No Different
5	Somewhat Easier
6	No Different
7	No Different
8	No Different – once I had learned the trajectory

7) Did you find that you:

Wanted more information___ Had enough information___

Please explain

Subject	Response
1	Had enough information
2	Had enough information
3	Wanted more information – I really wanted to see what my body was doing
4	Wanted more information – I was interested in force information – even just a warning bar that would highlight if I pressed too hard or if the moments in the drill task were too large
5	Had enough information
6	Had enough information
7	Had enough information
8	Wanted more information – yes, I very much wanted some force feedback – maybe audible rather than visible something simple like force magnitude

8) Please comment on the ideal type of display for the tasks you just completed:

Subject	Response
1	One which matches orientation – back view
2	None
3	I think they were both very useful. The capability to zoom in and out would have been helpful
4	A possibly reduced frontal view would be very useful for gross motions. The wrist view where the fingers turn different colors to indicate force would be useful. e.g. yellow to red for high forces
5	Perhaps force/torque readings
6	View #1 – front view of Robonaut View #2 – side view of Robonaut View #3 – view of hand WITH Joints turning red when they are close to a limit Parts turning orange when they are close to another part Fingers turning blue when they are applying pressure gradient
7	Single overlay of overall
8	A contact force vector either displayed (near center of FOV – very small) or audible

9) Please rank the utility of the displays that you saw, 1 being the most useful, 5 the least

_____Robonaut frontal view
_____Wrist view
_____Both displays
_____Frontal view with voice
_____ No display

Subject	Response – in order of preference – 1 (highest) to 5
1	Frontal view with voice, Robonaut frontal view, No display, Both displays, Wrist view
2	Frontal view with voice, Robonaut frontal view, No display, Wrist view, Both displays
3	Subject ranked no display a 2, and the frontal view, wrist and both a 4 – did not rank voice
4	Robonaut frontal view, Frontal view with voice, No display, Both displays, Wrist view
5	Frontal view with voice, Robonaut frontal view, No display, Both displays, Wrist view
6	Frontal view with voice, Robonaut frontal view, Both displays, No display, Wrist view
7	Frontal view with voice, Robonaut frontal view, No display, Both

	displays, Wrist view
8	Both displays, No display, Frontal view with voice, Robonaut frontal view, Wrist view

10) Please comment on any hardware problems that may have been experienced during the trials:

Subject	**Response**
1	
2	At one time I opened my hand to release the handrail and nothing happened
3	
4	
5	
6	Video dropout definitely affected performance
7	
8	Fingers were difficult to coordinate and fully retract

L.2.4 Additional Comments

Please comment on any aspect of the telerobotic experiment in particular:

Subject	**Response**
1	
2	The video in the helmet was a little fuzzy – make it difficult to align the drill
3	
4	The indexing definitely made a difference in how well I felt I could perform a task. If my arm was in an awkward position, the task seemed much more difficult. When it was in a good position, the tasks were very simple and straightforward. Overall it was very easy to learn the tasks and perform them with proficiency. There were a few times where I thought I missed the drill grasp but I was able to start over and successfully re-grasp
5	
6	Reach should be mapped to human min/max of human = min/max of Robonaut
7	No fatigue on last task because task involved large ranges of motion. Large range of head horizontal motion required for task due to limited camera FOV. Perhaps this could be scaled??
8	Force feedback (maybe audible) would allow the user to better interpret operation during contact – sometimes I didn't realize that the reason the thing wouldn't close was due to contact stall

Appendix M Design Iteration III Display Overlay Programs

Experiment B involved visual display aids that notified the user when either joint limits were exceed, or when the robot was put in a harmful position. Two programs were written in C++ to interface with the simulation. This code interrupted the simulation drawing routine and performed limit checks on the Polhemus data. If there a limit was exceed and an alert was necessary, the code altered the color of the hand, blue for chicken winging and red for self-collision, then sent that drawing command to the simulation routine, otherwise the data was passed through with the hand color unaltered.

M.1 Elbow Overlay

This overlay is designed to test if the elbow has been commanded to a height above the chest deemed harmful. If so, the hand is colored blue. In addition, data files are opened and trial data output to that file containing the value of the joint angles under investigation.

```
// AngleOverlay.cpp : Defines the initialization routines for the DLL.
//

#include "stdafx.h"
#include <afxdllx.h>

#ifdef _DEBUG
#define new DEBUG_NEW
#undef THIS_FILE
static char THIS_FILE[] = __FILE__;
#endif


static AFX_EXTENSION_MODULE AngleOverlayDLL = { NULL, NULL };

extern "C" int APIENTRY
DllMain(HINSTANCE hInstance, DWORD dwReason, LPVOID lpReserved)
{
 // Remove this if you use lpReserved
 UNREFERENCED_PARAMETER(lpReserved);

 if (dwReason == DLL_PROCESS_ATTACH)
 {
       TRACE0("ANGLEOVERLAY.DLL Initializing!\n");

       // Extension DLL one-time initialization
```

```
        if (!AfxInitExtensionModule(AngleOverlayDLL, hInstance))
                return 0;

        // Insert this DLL into the resource chain
        // NOTE: If this Extension DLL is being implicitly linked to by
        //  an MFC Regular DLL (such as an ActiveX Control)
        //  instead of an MFC application, then you will want to
        //  remove this line from DllMain and put it in a separate
        //  function exported from this Extension DLL.  The Regular DLL
        //  that uses this Extension DLL should then explicitly call that
        //  function to initialize this Extension DLL.  Otherwise,
        //  the CDynLinkLibrary object will not be attached to the
        //  Regular DLL's resource chain, and serious problems will
        //  result.

        new CDynLinkLibrary(AngleOverlayDLL);
 }
 else if (dwReason == DLL_PROCESS_DETACH)
 {
        TRACE0("ANGLEOVERLAY.DLL Terminating!\n");
        // Terminate the library before destructors are called
        AfxTermExtensionModule(AngleOverlayDLL);
 }
 return 1;   // ok
}


#include "hsl.h"

void MyAngle ( HLC_Node *pNodeA, HLC_Node *pCamera, HLC_Node *pWindow, ULong
drawFlagA );

SO_FunctionNames    FunctionData = {
 MyAngle,     //Draw Function
 NULL,        //Initialize Function
 NULL,        //NULL Function
 NULL,        //NULL Function
 NULL         //Delete Function
};

//Call function names from Enigma in C and convert for use here
extern "C" {
        __declspec(dllexport) SO_FunctionNames *
                GetFunctionData(void)
        {
                return( &FunctionData );
        }
}

HLC_Node      *pmin              = NULL;
HLC_Node      *LeftPalm          = NULL,
              *RightPalm         = NULL,
              *Chest             = NULL;

static MLC_Point3D p1,p2;
static MLC_Matrix4D invmatL;
float mindist;

void MyAngle ( HLC_Node *pNodeA, HLC_Node * /*pCamera*/, HLC_Node * /*pWindow*/,
ULong drawFlagA )
{
        static HLC_Node *RightElbow=NULL;
        static HLC_Node *pwingR=NULL;
        MLC_Model *pmodL;
        MLC_Matrix4D matL,cmatL;
        double dmatL[4][4];

//Initialize variables
        if (RightElbow      == NULL)
            RightElbow      = HLF_FindNode("Elbow_Pitch_R");
        if (pwingR          == NULL)
            pwingR          = HLF_FindNode("Shoulder_Pitch_R");
```

```
        if (Chest           == NULL)
            Chest           = HLF_FindNode("Spine_New");
        if (RightPalm       == NULL)
            RightPalm       = HLF_FindNode("palma3_rh.2");

        if (RightElbow      == NULL)
            return;
        if (pwingR          == NULL)
            return;
        if (Chest           == NULL)
            return;
        if (RightPalm== NULL)
            return;

//Get hand model data.  Call the elbow matrix, translate into the correct
//coordinate frame and test if elbow exceeds height limit above the chest
//if so, change right hand color
pmodL = pNodeA->GetModelPointer();

if(pmodL != NULL){

if
        (pNodeA == RightPalm){
        matL = RightElbow->GetMatrix(HLD_GLOBAL);
        matL.Get(dmatL);
                if
                        (dmatL[2][3] <= 7.2){
                        pmodL->Draw(drawFlagA, 0.0,0.0,1.0,0.0);
                        }
                        else
                                pmodL->Draw(drawFlagA);
                }
        }
                if(fpL ==NULL) fpL = fopen("trial.dat","w");
                fprintf(fpL,"ElbowPos = %f \n",(float)dmatL[2][3]);
                fflush(fpL);
}
```

M.2 Collision Overlay

This overlay is designed to test if the elbow or forearm has collided with the torso. If so, the hand is colored red. In addition, data files are opened and trial data output to that file containing the value of the joint angles under investigation.

```
// OverialSim.cpp : Defines the initialization routines for the DLL.
//

#include "stdafx.h"
#include <afxdllx.h>

#ifdef _DEBUG
#define new DEBUG_NEW
#undef THIS_FILE
static char THIS_FILE[] = __FILE__;
#endif


static AFX_EXTENSION_MODULE OverialSimDLL = { NULL, NULL };

extern "C" int APIENTRY
DllMain(HINSTANCE hInstance, DWORD dwReason, LPVOID lpReserved)
{
        // Remove this if you use lpReserved
```

```
        UNREFERENCED_PARAMETER(lpReserved);

        if (dwReason == DLL_PROCESS_ATTACH)
        {
                TRACE0("OVERIALSIM.DLL Initializing!\n");

                // Extension DLL one-time initialization
                if (!AfxInitExtensionModule(OverialSimDLL, hInstance))
                        return 0;

                // Insert this DLL into the resource chain
                // NOTE: If this Extension DLL is being implicitly linked to by
                //  an MFC Regular DLL (such as an ActiveX Control)
                //  instead of an MFC application, then you will want to
                //  remove this line from DllMain and put it in a separate
                //  function exported from this Extension DLL.  The Regular DLL
                //  that uses this Extension DLL should then explicitly call that
                //  function to initialize this Extension DLL.  Otherwise,
                //  the CDynLinkLibrary object will not be attached to the
                //  Regular DLL's resource chain, and serious problems will
                //  result.

                new CDynLinkLibrary(OverialSimDLL);
        }
        else if (dwReason == DLL_PROCESS_DETACH)
        {
                TRACE0("OVERIALSIM.DLL Terminating!\n");
                // Terminate the library before destructors are called
                AfxTermExtensionModule(OverialSimDLL);
        }
        return 1;   // ok
}

/* The preceeding code was written automatically with the creation of a new DLL
file */


#include "hsl.h"            //for IGOAL library//

void   MyDraw       ( HLC_Node *pNodeA, HLC_Node *pCamera, HLC_Node *pWindow,
ULong drawFlagA );

SO_FunctionNames    FunctionData = {
        MyDraw,             //Draw function will contain all mindist and color
                            changing calculations//
        NULL,               //Initialize function - here it does nothing//
        NULL,               //NULL function//
        NULL,               //NULL function//
        NULL                //Delete function - here it does nothing//
        };


//Call function names from Enigma in C and convert for use here
extern "C" {
        __declspec(dllexport) SO_FunctionNames *
                GetFunctionData(void)
        {
                return( &FunctionData );
        }
}

//Initialize variables
HLC_Node *pmin = NULL;
HLC_Node *LeftUpperArm     =     NULL,
         *LeftBicept       =     NULL,
         *LeftElbow        =     NULL,
         *LeftForearm      =     NULL,
         *RightUpperArm    =     NULL,
         *RightBicept      =     NULL,
         *RightElbow       =     NULL,
         *RightForearm     =     NULL;
```

```
//Overwtite draw function
void MyDraw (HLC_Node *pNodeA, HLC_Node * /*pCamera*/, HLC_Node * /*pWindow*/,
ULong drawFlagA)
{
       static HLC_Node *RightHand = NULL;
       static HLC_Node *RightElbow = NULL;
       static HLC_Node *RightForearm = NULL;
       MLC_Point3D p1,p2;
       float  mindist;
       MLC_Model *pmodL;

//Get model names
pmodL = pNodeA->GetModelPointer();
if(pmodL != NULL)
pmodL->Draw(drawFlagA);

//Initialize data files
static FILE *fpL=NULL;
static FILE *fsL=NULL;

//Assign code variable names to model node names
if (RightHand        ==     NULL)
    RightHand        =      HLF_FindNode("palma3_rh.2");
if (RightElbow       ==     NULL)
    RightElbow       =      HLF_FindNode("segment3_R");
if (RightForearm     ==     NULL)
    RightForearm     =      HLF_FindNode("segment4_R");

if (RightHand        ==     NULL)
    return;
if (RightElbow       ==     NULL)
    return;
if (RightForearm     ==     NULL)
    return;


//Calculate the minimum distance between elbow, forearm and body, change hand
//color to red if collision occurs if necessary. Also open data file and store
//minimum distance data for both elbow and forearm
RightElbow->FindMinDist(&mindist, &p1, &p2, &pmin);

if(fpL == NULL) fpL = fopen("ElbowColl.dat","w");
       fprintf(fpL,"ElbowMindist = %f\n",mindist);
       fflush(fpL);
if
       (mindist <= 0.03){
       RightHand->SetColor(1.0,0.0,0.0);
       RightHand->SetFlag(HLD_COLOR);
       }
else
       RightHand->ClearFlag(HLD_COLOR);

RightForearm->FindMinDist(&mindist, &p1, &p2, &pmin);

if(fsL == NULL) fsL = fopen("ArmColl.dat","w");
       fprintf(fsL,"ArmMindist = %f\n",mindist);
       fflush(fsL);
if
       (mindist <= 0.03){
       RightHand->SetColor(1.0,0.0,0.0);
       RightHand->SetFlag(HLD_COLOR);
       }
       else
              RightHand->ClearFlag(HLD_COLOR);

}
```

Appendix O Laboratory Experiment B Subjective Responses

The following appendix lists the subjective questions asked of the subject after each trial.

O.1.1 Fatigue Questions

1) Did you experience any fatigue or discomfort during the trials? If so, where (on body, or mental) and at what point during the test did this occur?

Subject	Response
1	Some fatigue, Top of Hand
2	Major fatigue, Temporal pain from HMD being front heavy. Right eye strain, had to close eyes between tasks
3	Some fatigue. Head, HMD
4	Some fatigue. Neck and head – latter part of test
5	No fatigue
6	Some fatigue. Top of head ~test 10
7	No fatigue
8	Some fatigue. Forearm – long trial early in test
9	Some fatigue. Hot head! Eye fatigue during "scene changes"
10	Some fatigue. Mental, neck – HMD heavy, ~trial 20
11	Some fatigue. Eye fatigue during middle of testing

2) What methods did you use to combat fatigue during the trials?

Subject	Response
1	Moved slower
2	Could not combat fatigue induced by the weight of the HMD. Closed eyes between tasks to reduce/stop eye strain
3	Took helmet off, flipped viewer down
4	Stretching
5	N/A
6	Removing helmet
7	Adjusting posture, moving head, resting hand between trials
8	Shaking my hand
9	Took helmet off occasionally. Mopped brow. Closed eyes during "scene changes"
10	Move neck during rests, close eyes
11	Eye rest between trials

O.1.2 Specific Task Questions

1) Please rate the overall difficulty of the **GREEN HANDRAIL – DISPLAY OFF** task, 1 being Very Easy and 5 being Very Difficult (circle one)

Subject	Response
1	4
2	2
3	3
4	2
5	2
6	3
7	2
8	3
9	2
10	2
11	1

2) Please elaborate on the level of difficulty:

Subject	Response
1	A few parts of the task were difficult, but most of the parts were easy
2	A few parts of the task were difficult, but most of the parts were easy
3	Half of the task was easy, half difficult
4	A few parts of the task were difficult, but most of the parts were easy
5	A few parts of the task were difficult, but most of the parts were easy
6	Half of the task was easy, half difficult
7	A few parts of the task were difficult, but most of the parts were easy
8	Half of the task was easy, half difficult
9	The entire task was easy
10	A few parts of the task were difficult, but most of the parts were easy
11	The entire task was easy

3) Which sections of the task did you find difficult and why?

Subject	Response
1	Turning my wrist just before grasping
2	Aligning the hand (grasp) in a vertical orientation to properly grasp the handle
3	Alignment of hand position to rail
4	Positioning my arm to achieve the desired final position of the robot
5	Alignment of the wrist so that I was perpendicular to the handrail was difficult w/o producing elbow problems
6	Farthest handrail. Tended to get ahead of the sim
7	Maintaining the correct wrist yaw. Trying not to overshoot handrail when grasping
8	Keeping the sim stable out at rail- it had a tendency to move around quite a bit
9	None especially difficult. Robot hand seemed to move more than my hand – exaggerated movements in x,y,z

10	Getting wrist oriented, trying to find distance moving entire head to look up
11	None of the sections for this task seemed difficult

4) Which sections of the task did you find easy, and why?

Subject	Response
1	Rotating my head to the right and looking for the correct target
2	Translating from the home position to the handrail location
3	Getting hand there
4	Gross alignment – natural motion
5	Getting the hand near the rail was easy
6	Easiest of the 3 handrails as far as depth perception – don't know why
7	Approaching handrail
8	Moving the arm to the spot, moving the head around
9	Intuitive control – I move my hand, robot moves hand similarly
10	Getting arm/hand in position
11	The entire task seems easy. It was a straight-forward trajectory to the handrail without too much worries above wrist angle and arm location

5) Did you find that the more times you did the task that the level of difficulty (circle one):

Subject	Response
1	Decreased
2	Decreased
3	Increased
4	Remained the same
5	Decreased
6	Remained the same
7	Remained the same
8	Decreased
9	Decreased
10	Remained the same
11	Decreased

6) Please explain the above response:

Subject	Response
1	I learned where to position my arm and head just before the experiment began. This made it easier to understand the position of the robot arm
2	Wrist orientation was very important in controlling the location of the elbow. I used wrist orientation to prevent elbow contact w/body while translating from home location to handrail location. Once in position, I would change wrist orientation to grasp handrail.
3	Once I did it "wrong" with the blue color, I was more critical of my movements in the future trials
4	My final arm configuration was always a little awkward
5	Particularly I learned the relative positions and max allowable speed over time
6	Always wanted to speed up

7	In some cases it seemed a little harder to orient the wrist, but it was independent of repetition
8	I settled into a pattern that worked well
9	Easier with practice to know where to move my hand to achieve desired motion of robot hand
10	I tried slightly different approaches to see if I could influence arm orientation – rotate hand first; move arm over first; lift arm first
11	After the initial trials, I grew accustomed to where and in what orientation the hand must be

7) Did you alter your strategy during the task at all during the course of the experiment?

Subject	Response
1	Yes. I learned to position my arm with respect to the robot arm
2	No
3	No
4	Yes. I tried positioning my hand closer to my hip at startup but did not seem to help the awkwardness of the final position.
5	Somewhat. I tried to minimize direction changes due to the lag of the hand – somehow straight fluid motions worked better
6	No
7	Yes. More attention was paid to the wrist yaw/pitch
8	Not consciously – I did learn how to better accomplish the task as the test went on
9	Yes. I'd move quickly to a mid-point near the target then slowly close the distance
10	See above
11	Yes. I discovered that I did not have to adjust the wrist angle very much, so I kept it to a minimum

8) Please rate the overall difficulty of the **GREEN HANDRAIL – DISPLAY ON** task, 1 being Very Easy and 5 being Very Difficult (circle one)

Subject	Response
1	4
2	N/A
3	3
4	3
5	2
6	4
7	2
8	4
9	2
10	3
11	1

9) Please elaborate on the level of difficulty:

Subject	Response
1	Half of the task was easy, half difficult
2	N/A
3	Half of the task was easy, half difficult
4	Half of the task was easy, half difficult
5	A few parts of the task were difficult, but most of the parts were easy
6	Most of the task was difficult, only a few parts were easy
7	A few parts of the task were difficult, but most of the parts were easy
8	A few parts of the task were difficult, but most of the parts were easy
9	The entire task was easy
10	A few parts of the task were difficult, but most of the parts were easy
11	The entire task was easy

10) Which sections of the task did you find difficult and why?

Subject	Response
1	Reaching high and rotating my arm just before grasping
2	N/A
3	N/A
4	Final positioning of the robot because the robot elbow always seemed to come away from the body and produce a "blue" warning
5	Same as above
6	Same as with display off – but in addition trying to avoid display coming on
7	Determining correction required when display was blue
8	Getting rid of the blue hand – it wanted to be blue no matter what I did
9	Same
10	Elbow orientation – seems like I would trigger display when I got the hand in a good position
11	Same as (3)

11) Which sections of the task did you find easy, and why?

Subject	Response
1	Looking for the handrail with respect to the display
2	N/A
3	Same as above
4	Gross positioning – natural motion
5	Same as above
6	Same as (4)
7	Approaching handrail
8	Moving the heard, turning the arm, relocating the arm to the rail
9	Same
10	Getting to the right position (but difficulty increase trying to keep display from triggering
11	Same as (4)

12) Did you find that the more times you did the task that it's level of difficulty (circle one)

Subject	Response
1	Decreased
2	N/A
3	Increased
4	Remained the same
5	Decreased
6	Remained the same
7	Decreased
8	Decreased
9	Decreased
10	Remained the same
11	Decreased

Please explain the above response:

Subject	Response
1	I was able to locate the handrail faster
2	N/A
3	Same as "off"
4	Never could find a reliable way to prevent the "blue" warning
5	N/A
6	Sometimes hand/arm out of whack
7	Response to display improved making the task easier
8	I learned how better to do the task
9	It became easier to figure out how to move my hand to avoid "blue" hand
10	Tried different approaches – so each trial was different
11	Same as (5)

13) Did you alter your strategy during the tracing task at all during the course of the experiment?

Subject	Response
1	I slowed my movement of my arm and kept my wrist from moving too much
2	N/A
3	No
4	Yes. I conducted an early wrist roll to keep the robot elbow tight to its side but was not reliable
5	I tried to minimize wrist orientation changes to keep the elbow "happy"
6	No. Saw no way of helping
7	Yes. Watched the pitch and yaw of the wrist and tried to keep the elbow down to prevent display warning
8	Yes. Came up from underneath after the debacle of my first trial
9	Yes. Same as green-off

10	See above
11	Same as (7)

14) Please rate the overall difficulty of the **PINK HANDRAIL – DISPLAY OFF** task, 1 being Very Easy and 5 being Very Difficult (circle one)

Subject	**Response**
1	3
2	1
3	1
4	1
5	1
6	2
7	1
8	1
9	1
10	4
11	2

15) Please elaborate on the level of difficulty:

Subject	**Response**
1	A few parts of the task were difficult, but most of the parts were easy
2	The entire task was easy
3	The entire task was easy
4	The entire task was easy
5	The entire task was easy
6	A few parts of the task were difficult, but most of the parts were easy
7	The entire task was easy
8	The entire task was easy
9	The entire task was easy
10	Most of the task was difficult, only a few parts were easy
11	The entire task was easy

16) Which sections of the task did you find difficult and why?

Subject	**Response**
1	Reaching high enough and rotating my arm
2	N/A
3	N/A
4	N/A
5	N/A
6	Height of handrail
7	Initially the approach was a little difficult with the lack of depth perception
8	N/A
9	One time I had trouble because robot moved more than my hand did
10	Difficult judging location of handrail. Difficult moving hand down – seemed

	to want to take off upwards
11	The only difficult part was maintaining a straight wrist angle during hand approach. The handle seemed further away at times, but that may be due to the initial start position.

17) Which sections of the task did you find easy, and why?

Subject	**Response**
1	Looking for the handrail
2	Translating from home to final location
3	N/A
4	Basically the entire task was very natural
5	N/A
6	Head motion – straight ahead
7	Grabbing handrail – easy hand position/orientation
8	All of it
9	Easy approach, no reach limits to worry about
10	Orientation was easy
11	To move to the handle because it is a relatively straight trajectory

18) Did you find that the more times you did the task that it's level of difficulty (circle one)

Subject	**Response**
1	Remained the same
2	Decreased
3	Remained the same
4	Remained the same
5	Decreased
6	Decreased
7	Decreased
8	Remained the same
9	Decreased
10	Remained the same
11	Remained the same

Please explain the above response:

Subject	**Response**
1	N/A
2	Very little possibility of elbow collision during this task. Simply command arm to move in straight line
3	N/A
4	Never had difficulty with the task
5	Very easy -> extremely easy
6	Adapted to height of handrail
7	Once the depth of handrail was determined (location), it was much easier to

	perform the task
8	Easy task stayed easy
9	I learned where to position my hand to get close to target
10	Never was able to get a handle on vertical location
11	I did not notice any big difference

19) Did you alter your strategy during the task at all during the course of the experiment?

Subject	**Response**
1	I slowed my movement of my arm and kept my wrist from moving too much
2	N/A
3	No
4	No
5	Not really
6	Yes. After first attempt, made sure to move higher before approach
7	Yes. Again, watched the wrist pitch and tried to move more to the left when grasping the handrail
8	No. It was pretty straightforward
9	Yes. I quickly moved my hand close to target then slowly closed the distance
10	Yes. Tried going forward first, tried going up or down first
11	Yes. My approach was different from the beginning in order to grasp the handle better.

20) Please rate the overall difficulty of the **PINK HANDRAIL – DISPLAY ON** task, 1 being Very Easy and 5 being Very Difficult (circle one)

Subject	**Response**
1	3
2	N/A
3	1
4	1
5	1
6	2
7	1
8	1
9	1
10	4
11	2

21) Please elaborate on the level of difficulty:

Subject	**Response**
1	A few parts of the task were difficult, but most of the parts were easy
2	N/A
3	The entire task was easy
4	The entire task was easy
5	The entire task was easy

6	A few parts of the task were difficult, but most of the parts were easy
7	The entire task was easy
8	The entire task was easy
9	The entire task was easy
10	Most of the task was difficult, only a few parts were easy
11	The entire task was easy

22) Which sections of the task did you find difficult and why?

Subject	Response
1	Reaching high enough and out
2	N/A
3	N/A
4	N/A
5	N/A
6	Same as (16)
7	Fairly easy to perform task
8	N/A
9	Same as pink-off
10	Similar to w/o display – perhaps a little more difficult due to worrying about elbow
11	Same as (16). I believe I only violated the elbow orientation 1 or 2 times. The improvement may have been due to my change in approach

23) Which sections of the task did you find easy, and why?

Subject	Response
1	Locating the handrail
2	N/A
3	N/A
4	All tasks were natural
5	N/A
6	Orientation was easy to keep b/c handrail was directly in front
7	Approach and grasping
8	The whole task
9	Same as pink-off
10	Hand orientation – mostly straightforward
11	Same as (17)

24) Did you find that the more times you did the task that it's level of difficulty

Subject	Response
1	Remained the same
2	N/A
3	Remained the same
4	Remained the same
5	Decreased

6	Decreased
7	Decreased
8	Remained the same
9	Decreased
10	Remained the same
11	Remained the same

Please explain the above response:

Subject	Response
1	N/A
2	N/A
3	N/A
4	Never had difficulty with the task
5	Very easy -> extremely easy
6	Same as (18)
7	Again, knowing the depth of handrail from the first approach made additional runs easier
8	It started easy, it stayed easy
9	Same as pink-off
10	Trouble with "distance, pos" of handrail, no depth cues
11	Same as (18)

25) Did you alter your strategy during the tracing task at all during the course of the experiment?

Subject	Response
1	N/A
2	N/A
3	No
4	No. No need to change
5	No
6	Yes. Same as (19)
7	Yes. Attempted to stay more toward the left side of the handrail when grasping
8	No
9	Same as pink-off. The display didn't make any difference for pink
10	Yes. Forward first, up or down first …
11	Yes. Same as (19)

26) Please rate the overall difficulty of the **YELLOW HANDRAIL – DISPLAY OFF** task, 1 being Very Easy and 5 being Very Difficult (circle one)

Subject	Response
1	4
2	3

3	2
4	1
5	2
6	2
7	2
8	2
9	2
10	1
11	2

27) Please elaborate on the level of difficulty:

Subject	Response
1	A few parts of the task were difficult, but most of the parts were easy
2	Half of the task was easy, half difficult
3	A few parts of the task were difficult, but most of the parts were easy
4	The entire task was easy
5	A few parts of the task were difficult, but most of the parts were easy
6	A few parts of the task were difficult, but most of the parts were easy
7	A few parts of the task were difficult, but most of the parts were easy
8	A few parts of the task were difficult, but most of the parts were easy
9	A few parts of the task were difficult, but most of the parts were easy
10	A few parts of the task were difficult, but most of the parts were easy
11	The entire task was easy

28) Which sections of the task did you find difficult and why?

Subject	Response
1	Moving my arm across my body and reaching out far enough to grasp the handrail
2	Positioning the hand over the handrail. Left and right images of the handrail appeared to be in different locations
3	Most of the task was easy except when depth perception made rail look higher than it was
4	N/A
5	Required reaching down significantly
6	Depth was harder than green but easier than white
7	Bringing the arm into position without yawing the wrist
8	The depth perception on the task was more difficult than the others
9	It was a little difficult to avoid the white and black pad
10	Wrist orientation was sometimes difficult. One difficult session where initialization was off I had to press into my body to get close
11	Maintaining a straight wrist angle due to the position of the handrail with respect to the arm

29) Which sections of the task did you find easy, and why?

Subject	Response
1	Moving my arm up
2	Translating from home position to handrail location. Straight shot, no difficult movements necessary
3	N/A
4	The entire task was natural
5	Reaching over was easy
6	No worries about orientation (display being off)
7	Grasping – once the arm was in a good position, it was easy to perform the final alignment
8	The rest of it
9	N/A
10	Location, position of handrail was easy
11	The approach to the handrail because it seemed straight forward

30) Did you find that the more times you did the task that it's level of difficulty (circle one) Increased Remained the Same Decreased

Subject	Response
1	Remained the same
2	Decreased
3	Decreased
4	Remained the same
5	Decreased
6	Remained the same
7	Remained the same
8	Increased
9	Decreased
10	Remained the same
11	Remained the same

Please explain the above response:

Subject	Response
1	It was difficult to reach out far. I couldn't tell how far out the handrail was and found myself reaching out very far
2	Because of the disparity in apparent handrail location I closed my left eye while trying to grasp the handrail. The grasping task became easier once I started using that technique
3	N/A
4	Simply an easy task
5	I learned to head straight toward the rail
6	No way to improve
7	Some runs were easier to position the arm than others – independent of repetition

8	The depth perception problem didn't seem to bother me as much in the early trials
9	Again, I moved my hand to a half-way point then slowly closed the gap
10	Relatively simple task remained relatively simple
11	No big difference

31) Did you alter your strategy during the task at all during the course of the experiment? Please explain:

Subject	Response
1	No
2	Yes. Closed eye as explained above
3	N/A
4	No. No need to alter strategy
5	Yes. See above
6	No. No way to improve
7	Yes. Tried to keep wrist yaw straight
8	No
9	No
10	Simple task – did not need to altar strategy
11	No

32) Please rate the overall difficulty of the **YELLOW HANDRAIL – DISPLAY ON** task, 1 being Very Easy and 5 being Very Difficult (circle one)

Subject	Response
1	4
2	N/A
3	2
4	1
5	2
6	2
7	2
8	2
9	2
10	2
11	4

33) Please elaborate on the level of difficulty:

Subject	Response
1	A few parts of the task were difficult, but most of the parts were easy
2	N/A
3	A few parts of the task were difficult, but most of the parts were easy
4	The entire task was easy

5	A few parts of the task were difficult, but most of the parts were easy
6	A few parts of the task were difficult, but most of the parts were easy
7	A few parts of the task were difficult, but most of the parts were easy
8	A few parts of the task were difficult, but most of the parts were easy
9	A few parts of the task were difficult, but most of the parts were easy
10	A few parts of the task were difficult, but most of the parts were easy
11	Half of the task was easy, half difficult

34) Which sections of the task did you find difficult and why?

Subject	Response
1	Moving my arm across my body and reaching out far enough
2	N/A
3	Same as above
4	N/A
5	Sometimes it was difficult to reach w/o elbow problems due to the long distance
6	Orientation a little difficult b/c handrail close to body
7	Approaching while preventing self-contact
8	Same as previous
9	The display didn't seem to help much. Again, difficult approach
10	Elbow collisions added to difficulty
11	Balancing a straight wrist angle versus elbow collision kept conflicting

35) Which sections of the task did you find easy, and why?

Subject	Response
1	Moving my arm up
2	N/A
3	Same as "off"
4	The entire task was natural
5	Near final grasp – proper elbow placement
6	Orientation was easier to correct than green handrail task w/display
7	Grasping handrail once positioned
8	Same
9	N/A
10	Location, hand/arm position was easy
11	Initial approach and hand alignment to the handle seemed straight forward

36) Did you find that the more times you did the task that it's level of difficulty (circle one)

Increased Remained the Same Decreased

Subject	Response
1	Remained the same
2	N/A
3	Decreased

4	Remained the same
5	Decreased
6	Remained the same
7	decreased
8	Increased
9	Decreased
10	Remained the same
11	Remained the same

Please explain the above response:

Subject	Response
1	N/A
2	N/A
3	Seemed like when I knew a yellow was coming I could index my head to the left – helped with depth perception
4	Simply an easy task
5	I learned to maintain a smooth/optimal trajectory
6	No way to improve
7	After seeing the display once or twice, it became easier to respond and/or anticipate self-contact conditions
8	Depth perception got worse
9	N/A
10	Simple task – remained simple
11	The problems I had remained consistent between each trial

37) Did you alter your strategy during the tracing task at all during the course of the experiment? Please explain:

Subject	Response
1	No
2	N/A
3	Yes. Concentrated on where to index my head prior to the start of the test
4	No. No need to alter strategy
5	See above
6	No. No way to improve
	Yes. Tried to keep the arm further away from the body while approaching
8	No
9	No
10	No. No need to altar strategy.
11	Yes. I tried different ways to achieve proper wrist angle while avoiding elbow collision. But it seemed the wrist had to be bent more than the other trials

O.3 Polhemus and Display Questions

1) Did the Polhemus trackers track your movements adequately:
Not At All   Some of the time   Half the time   Most of the time   Always

Subject	Response
1	Always
2	Most of the time
3	Most of the time. Seemed misaligned on one run – axis seemed shifted. Might have been where I indexed to start
4	Most of the time
5	Most of the time
6	Most of the time
7	Most of the time
8	Most of the time
9	Most of the time
10	Most of the time
11	Most of the time

2) Did the above answer depend on the speed at which you were moving:

Subject	Response
1	Tracked better when I moved more slowly
2	Tracked better when I moved more slowly
3	Tracked better when I moved more slowly
4	Tracked better when I moved more slowly
5	Tracked better when I moved more slowly
6	Tracked better when I moved more slowly
7	Tracked better when I moved more slowly
8	Tracked better when I moved more slowly
9	Tracked better when I moved more slowly
10	Tracked better when I moved more slowly
11	Tracked better when I moved more slowly

3) Did the ability of the Polhemus to track depend on the movements you were doing? If so, describe the types of movements (straight line, curved, planar, etc.) that caused it to:
Track Well:

Subject	Response
1	It tracked well
2	Did not notice that movements affected the accuracy of the Polhemus
3	N/A
4	When reaching in front it worked very well
5	Continuous/
6	Straight line – orientation
7	Straight line, wrist pitch/yaw
8	N/A

9	Slow
10	Straight line, planar movements
11	No discernable difference between trajectories

Track Poorly:

Subject	Response
1	N/A
2	N/A
3	N/A
4	When reaching out for the green handrail
5	N/A
6	Fast motion
7	Coarse motions with arm
8	N/A
9	Fast
10	Orientations of arm/wrist
11	N/A

4) Do you feel that you had all of the information that you needed to complete the task?

Subject	Response
1	N/A
2	Yes
3	Yes
4	Yes
5	Yes. Need to stress initial hand orientation more since it has such a major effect
6	Yes
7	Yes
8	Yes
9	No, I didn't always know how far it was from my robot hand to the target
10	Yes
11	Yes

Please comment on the overall usefulness of the displays

Red Collision Warning:

Not at all Useful Somewhat Useful Very Useful

Subject	Response
1	Very useful
2	N/A
3	Very useful
4	Very useful
5	Somewhat useful – probably necessary to protect arm
6	Somewhat useful

7	Very useful
8	Very useful
9	Not at all useful
10	Very useful
11	Very useful

Blue Joint Limit Warning:
Not at all Useful Somewhat Useful Very Useful

Subject	Response
1	Very useful
2	N/A
3	Very useful
4	Very useful
5	Somewhat useful – probably necessary to protect arm
6	Somewhat useful
7	Very useful
8	Very useful
9	Somewhat useful
10	Somewhat useful
11	Very useful

5) Did you ever ignore the displays? At what points or for what tasks?

Subject	Response
1	Didn't notice the displays
2	N/A
3	No
4	No
5	No
6	Tried not to but did after end of bad green handrail run
7	No
8	Only on the first green test, after you told me to do so [failed trial]
9	I didn't pay much attention to the red/blue graphics – I concentrated on getting the task done, knowing that the hand-holds were within reach, so I knew that grabbing a hand-hold would "fix" my red/blue "problem"
10	No, did not ignore. I always found myself trying to remove warning – sometimes to the detriment of completing task
11	No

6) What about the display did you find useful?

Subject	Response
1	N/A
2	N/A

3	Colors worked well to indicate attention needed
4	Definitely was an immediate indication that something was wrong. I liked not having to look somewhere else to get the indication. I was generally always concentrating on the hand
5	N/A
6	Pitch error helped for orientation
7	Both displays were immediate indicators of a condition that required attention while not blocking the view of the task worksite
8	On Robonaut, there's no feedback when the arm is chicken winging. It just acts funny. The sim still acts funny, but at least it tells you why
9	All useful, except red
10	Showed when there was a collision or an elbow limit
11	The display gave me valuable feedback so that I did not always have to look at the arm

7) What about the display did you find useless?

Subject	**Response**
1	N/A
2	N/A
3	N/A
4	Nothing
5	I actually found it to be annoying but probably a necessary annoyance since otherwise you may overstress the arm
6	Didn't help when whole arm was out
7	With the joint limit, it was evident from the display that the condition had occurred, but it was difficult to determine which joint and the response required
8	N/A
9	Red didn't seem to help any
10	Difficult to figure out what to do to alleviate warning
11	The display told me when something is about to occur, but not how it got into that situation. It was an all-encompassing warning

8) What improvements can you suggest to such a display?

Subject	**Response**
1	None
2	None
3	Allow view of robot after one of the warnings to allow for ease of correction
4	Indicate on the display what corrective action should be taken to correct error
5	Shades of color proportional to your nearness to an elbow violation
6	N/A
7	N/A
8	Perhaps put outlines on the handrails
9	Add "range to target" when appropriate. Allow alternate view angles to see operation from different point of view's

10	Only to add elbow control (pitch plane)
11	Perhaps provide more detailed information on the offending problem and suggest ways to back out

9) When you had **no display**, did you find the task:

Easier Somewhat Easier No Different Somewhat Harder Harder

Subject	**Response**
1	No different
2	No different
3	Somewhat Harder
4	Somewhat Easier
5	Somewhat easier. But probably only because I wasn't even aware of elbow violations
6	Somewhat easier
7	Somewhat harder. Harder to recognize limit conditions with arm, although without the display, it was easy to assume the arm position was fine and continue with the task. With the display though additional time was required to evaluate limits
8	Somewhat easier. Because I could stretch the limits a little more, I was trying to complete the task, not trying to make the hand white
9	No different
10	Somewhat easier
11	Easier

When you had the **display on**, did you find the task:

Easier Somewhat Easier No Different Somewhat Harder Harder

Subject	**Response**
1	No Different
2	No Different
3	Somewhat Easier
4	Somewhat Harder
5	Somewhat harder (see above)
6	Somewhat harder
7	Somewhat easier. Easier to detect limits
8	Somewhat Harder. While the display is useful, it does cause the operator to shift his attention to fixing the display instead of grabbing the handrail
9	No different
10	Somewhat harder
11	Somewhat harder

10) Did you find that you:

Wanted more information___ Had enough information___

Please explain

Subject	Response
1	Had enough information
2	Had enough information
3	Wanted more information. When no display, wanted color display of problem, with display, wanted display of robot to see if fixing worked. Because I didn't know prior whether the display was on or not, I assumed it was off. That worked OK until I got some warnings – then I was more critical of my actions and began to want the display. If I saw no color, I started to think I was ok and relied on whether the color was there. That could have given me a false sense of security in learning from "no display" tests. Throughout course of test, I began to rely on display and assume it was always on.
4	Wanted more information. More info about where hand is relative to handrail and how to correct errors
5	Wanted more information. Again, shades as you get near a violation
6	Had enough information
7	Wanted more information. Additional joint limit information may be helpful – which joint has the limit
8	Wanted more information. Only in the cases where depth perception was difficult
9	Had enough information
10	Had enough information
11	Wanted more information. See (7) and (8)

11) Please comment on the ideal type of display for the tasks you just completed:

Subject	Response
1	N/A
2	Some indication of elbow position without having to look at your elbow, i.e., video overlay of a wire frame model
3	Always "on"
4	Ideal for the hand to turn green when the ready-for-grasp is achieved. Status on the position of the elbow either by having a wider field of view or a display in the corner. A display that could freeze/thaw that is ratcheted so head was always in a comfortable position
5	See above
6	POR difference between hand and handrail
7	
8	It would light up when you had the handrail grasped
9	Could show a ghostly "approach corridor" and my position relative to it.

	Could show "ready to grasp" indicator when my hand is in position. See #8
10	If collision or joint limit – highlighting joint perhaps indicating which way to drive to alleviate warning
11	See (7) and (8). Additional information (not overwhelming) would be nice (such as joint angles)

O.4 Additional Comments

Please comment on any aspect of the experiment that you wish to elaborate on, suggestions you may have, or comments:

Subject	Response
1	Before the experiment began I learned that I had to position my head to the left depending on handrail I was reaching for. Holding my arm at a relaxed position made the arm chicken wing more often (i.e. I positioned my arm further into my side)
2	HMD weight caused a great deal of fatigue
3	N/A
4	Never encountered warnings on yellow or pink handrails. Helmet provided okay depth cues but not sufficient to avoid all collisions.
5	N/A
6	A little sponge for the crown of the helmet. An elbow sensor or forearm and upper arm sensor would help to match arm. Otherwise, simulation performed very responsively.
7	
8	N/A
9	How about a floor fan?
10	Head display is taxing (heavy). Depth perception was poor. Need to watch what position one's hand/arm is in for initialization
11	The most problem I had was elbow collision. It would be better If my elbow position was being tracked as well to better fix offending arm positions

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