SENSORY SUBSTITUTION FOR FORCE FEEDBACK IN SPACE TELEOPERATION

by

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Submitted to the Department of
Mechanical Engineering
in Partial Fulfillment of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY
IN MECHANICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June, 1992

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ABSTRACT

The objective of this research was to study the capabilities of sensory substitution (SS) for force feedback, presented to the operator of a teleoperation system, through the tactile and auditory senses, with and without a time delay. Traditional bilateral force feedback (FFB), which applies forces to a human operator's hand or arm muscles, has been shown in several studies to be beneficial to a person performing remote manipulation tasks. However, FFB can have its disadvantages. Systems which provide FFB are often bulky and costly, making them impractical in many environments, particularly in space. Further, presenting FFB in the presence of even small time delays creates operator induced instabilities. SS for force feedback can display force information without the disadvantages of FFB.

The major contributions of this thesis are: 1) an experimental study of the use of SS for force feedback through auditory and vibrotactile displays, which included psychophysical tests and remote manipulation tasks; 2) a solution to the problem of instability that occurs when providing force feedback in the presence of a time delay; 3) methods by which many remote tasks can be performed when both useful visual feedback and FFB are not available, and 4) general analyses that relate the effectiveness of SS to the quality and characteristics of available feedback, and to the nature of the task.

Performance was improved by using the SS displays when the representation of basic force information was tested through object contact experiments. Further, both of the SS displays compared favorably to FFB for representing this force information. SS was also found to improve the operator's sensitivity for detecting small forces by allowing the use of high feedback gain, without slowing movements or risking instabilities as would occur if FFB were used with high feedback gain. Common manipulation tasks conducted with a three second time delay determined that both of the SS displays significantly improved performance, and provided for stable teleoperation. When the operator's view was obstructed, the manipulation tasks were completed successfully both with and without a time delay while the subjects used either of the SS displays as the only source of feedback.

The usefulness of SS and its comparability to the performance of FFB, were dependent upon the quality of available visual feedback, the characteristics of the FFB, and the complexity of the information displayed through SS. Conclusions and recommendations for the successful use of SS for force feedback in teleoperation are also included.

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ACKNOWLEDGEMENTS

Special thanks to my advisor, Prof. Thomas Sheridan, for his support and guidance, and for challenging my abilities and keeping my best interest at heart throughout my education at MIT. Many thanks also to my doctoral program committee: Prof. Harold Alexander, Prof. Richard Held, and Nathaniel Durlach, for all of their help over the past four years. A special thank you also goes to Prof. David Akin of the University of Maryland, who was instrumental in getting my doctoral program started.

Several sponsors have made my education at MIT and this research possible: the NASA Graduate Student Researchers Program (Grant #NGT-50145), the MIT Zakhartchenko Fellowship, the NASA Jet Propulsion Laboratory (Contract # 956892), and Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI).

My deep gratitude goes to the four people who generously donated their valuable time to serve as test subjects for the experiments conducted in this thesis: Cliff Federspiel, Sean Li, Carola Massimino, and Mohamed Yahiaoui.

Many of my fellow students at MIT added to the educational experience at MIT and made it more enjoyable through their friendships. These friends include: Djamil Boulahbal, Forrest Buzan, Greg Chamitoff, Shih-Ken Chen, Chi-Cheng Cheng, Kan-Ping Chin, Cliff Federspiel, Dan Geisling, Chris Howell, Caleb King, Sean Li, Dan Merfeld, Knox Millsaps, Dava Newman, Jong Park, Nick Patrick, Jie Ren, Dave Schloerb, Mohamed Yahiaoui, Wael Yared, and Shumei Yin.

Many members of the MIT faculty and staff provided assistance during the completion of my degree including Norman Berube, "Tiny" Caloggero, Ted Coleman, Prof. Will Durfee, Norman MacAskill, Bob Nuttall, Dr. Bill Rabinowitz, Leslie Regan, and Bob Samuel.

Thanks also go to Nick Patrick, of the MIT Man-Machine Systems Lab, and Dave Franklin, of Audiological Engineering Corp. in Somerville, MA, for providing equipment used in this thesis.

A very special thank you goes to my parents, brothers, sisters, and in-laws for all of their emotional support during my six years at MIT and throughout my life.

Most of all I thank my wife Carola for putting up with me while I was completing this degree, and for always encouraging me to pursue my dreams.

1. INTRODUCTION

1.1 Motivation and Contributions

Bilateral master-slave force feedback, i.e. traditional force feedback, has been shown to be preferable to non-force feedback in many teleoperation studies [Massimino and Sheridan, 1989]. Hill and Salisbury [1977] found that for peg-in-hole tasks, completion times were significantly shorter with force feedback than without force feedback. Further, Hill [1979] concluded that difficult tasks were done twice as fast when force feedback was present. Force cues have also been shown to improve the accuracy of positioning a control stick or manipulator arm [Bahrick, 1957].

However, providing bilateral force reflection in the form of a force to the operator's arm and hand muscles can have its disadvantages. Systems that provide force feedback are often bulky master/slave manipulators that are impractical in many environments, particularly in space. Further, presenting this traditional force feedback to the operator's hand or arm in the presence of even small time delays has been shown to create operator induced instabilities. Ferrell [1966] suggested that the advantages of force sensitivity could be maintained in the presence of a time delay if the force feedback were substituted through the auditory or tactile modalities, and that a tactile display to the active hand might be especially compatible.

The major contributions of this thesis are: 1) an experimental study on the use of sensory substitution for force feedback through vibrotactile and auditory displays, which included psychophysical and remote manipulation tests, 2) a solution to the problem of instability that occurs when force feedback is provided in the presence of a time delay, 3) methods by which many remote tasks can be performed when both useful visual feedback and traditional bilateral force feedback are not available, and 4) general analyses that relate the effectiveness of sensory substitution to the quality and characteristics of available feedback, and to the nature of the task.

Bach-y-Rita, Webster, Tompkins, and Crabb [1987] define sensory substitution as "the provision to the brain of information that is usually in one sensory domain (for example visual information via the eyes and visual system) by means of the receptors, pathways and brain projection, integrative and interpretative areas of another sensory system, (for example visual information through the skin and somatosensory system). Some examples include sign language for the deaf, and Braille for the blind." Sensory substitution has been successfully used for many years in helping people who are fully or partially deficient in one or more of their sensory systems [Mann, 1974].

The tactile, in particular vibrotactile, and auditory modalities were of interest for several reasons. First, they provided non-reactive representations of force feedback. Non-reactive means sense modalities that do not induce operator movements like bilateral force feedback does when providing force information. Such movements may be undesirable in certain situations, and can cause instabilities in the presence of a time delay. In addition, the ears and the fingertips contain sensitive sensory receptors and are allocated relatively large areas in sensory cortex for information processing [Barlow and Mollon, 1982], suggesting that auditory and vibrotactile displays could be successful in presenting force feedback information. Further, the auditory and vibrotactile modalities can present force information while not placing any extra burden on the operator's visual system which is normally intently viewing the remote task environment via television monitor.

While conducting research on pilot display systems in aircraft, Doll and Folds [1985] noted that auditory displays posed several advantages over visual displays in presenting supplementary information to the operator. These advantages can also be applied to vibrotactile displays. They included presenting information irrespective of head position and direction of gaze, reducing the need to scan instruments visually which increased the speed with which an operator can react to emergency conditions, and requiring no extra space on what could already be a crowded control panel. Using auditory or vibrotactile sensory substitution of force feedback would therefore use sensory information that supplements visual feedback information, which has been identified as a critical teleoperation development challenge [Bejczy, 1977].

Vibrotactile and auditory displays may also provide cost benefits by reducing the need for expensive bilateral force reflecting manipulators. Further, sensory substitution may also reduce the need for expensive or complicated visual systems. Massimino and Sheridan [1989] showed that force feedback could decrease the need for visual feedback, since force feedback combined with low frame rate conditions (3 frames per second) provided performance that was comparable to performance under high frame rate conditions (30 frames per second) without force feedback. In addition, Bliss, Hill, and Wilber [1971] concluded that the utility of tactile feedback increased under poor visual conditions, and provided highly useful information that required a relatively low bandwidth channel. Thus a potential benefit of vibrotactile or auditory feedback is a possible reduced need for high quality visual feedback which could lead to decreased cost of teleoperation.

1.2 Objectives

To meet the major research objectives of this thesis, several groups of experiments were conducted. The first objective was to obtain information on the operating characteristics of the sensory substitution displays and of traditional force feedback. These characteristics provide information about the experimental system to researchers whose systems may have different characteristics. Further, it was hoped that these characteristics would lead to insights on performance differences that might occur during the teleoperation tasks. To accomplish this first objective, psychophysical tests were conducted.

The next objective was to determine the usefulness of sensory substitution for representing basic force information, such as the presence and magnitude of a force, and information to enable the sustained tracking of a contact force on an object. Therefore, object contact experiments that tested this basic force information were conducted.

A third objective was to study the ability of sensory substitution to represent the direction of a force during common manipulation tasks of varying difficulty. Peg-in-hole tasks of varying difficulty were conducted to meet this objective. Further, it was desired to measure the usefulness of sensory substitution under varying visual conditions. Therefore, the peg-in-hole tasks were conducted with unobstructed and obstructed views.

An additional objective was to determine the utility and stability of sensory substitution for force feedback in the presence of a time delay. In order to meet this objective, the peg-in-hole tasks were conducted with and without a three second time delay.

The final objective was to analyze the experimental results in order to provide explanations and theories for understanding the effects of sensory substitution. These analyses provide guidelines for future applications through general descriptive models. The usefulness of sensory substitution and its comparability to performance with traditional force feedback, were related to the quality of available visual feedback, the characteristics of traditional force feedback, and the complexity of information presented through sensory substitution.

1.3 Thesis Preview

The next chapter in this thesis provides some background on related research areas. The third chapter provides an overview of the hardware and software in the testbed that was used to conduct the experiments. Chapter four outlines initial psychophysical experiments that investigated the number of just noticeable differences (JND's) and the channel capacity of the human operator when using each of the sensory substitution displays. The object contact experiments and their results are presented in chapter five, while chapter six contains the experimental procedures and results for the peg-in-hole experiments. An additional psychophysical experiment, related to the peg-in-hole experiments, is also presented in chapter six. The investigation and experimental results for time delayed teleoperation is discussed in chapter seven. Chapter eight provides a brief review and summary of all of the teleoperation experimental results. An analysis of the usefulness of presenting sensory substitution in combination with visual feedback is presented in chapter nine, along with two additional informal experiments which were conducted to help reinforce the theories that were developed. The effects of replacing traditional force feedback with either of the sensory substitution displays are analyzed in chapter 10. Also included in chapter 10 are two additional psychophysical experiments which further investigated the capabilities of traditional force feedback, and helped to further analyze the teleoperation experimental results. Conclusions and recommendations are presented in chapter 11.

2. RESEARCH BACKGROUND

This chapter reviews past research on sensory substitution, auditory displays, and vibrotactile displays. It includes reviews of research on sensory substitution in physical rehabilitation and on sensory substitution for force feedback in teleoperation through visual displays. Previous work on the development of bisensory information processing theories were also reviewed, and led to insights into the experimental results found in this thesis.

2.1 Auditory Displays

Vision plays such an active and stimulating role in our daily lives that often the powerful abilities of our auditory systems go unnoticed. Our reaction time is faster to a sound (or to a tactile) stimulus than to a light stimulus [Welch and Warren, 1986]. Further, we have a keen ability to detect the direction of sound through binaural discrimination, as well as being able to discriminate sounds due to differences in loudness and pitch [Goldstein, 1989]. The next few sections provide examples of the usefulness of various auditory displays.

2.1.1 Auditory Displays for Sensory Substitution in Aircraft

As early as 1936, it was demonstrated that blindfolded pilots could fly airplanes when two of their instrument indications were presented aurally [deFlorez, 1936]. At that time it was apparent that a pilot was dependent on external visual references to maintain flight under clear weather conditions. In fog, researchers noticed that even the most experienced pilot could not maintain a proper orientation without suitable instruments. Even birds were shown to be dependent on their sight to maintain proper orientation in the sky. Visual or instrument flying can be a great burden on the visual system for even the most experienced instrument pilot. The workload can be substantial when considering the pilot's need to translate various instrument display readings into control inputs while also monitoring his/her position over the ground. Further, a pilot is also aware of the many dangers that may go undetected if not noticed visually such as the appearance of other aircraft or obstacles or the need to monitor fuel consumption, map readings, or weather information. Similar burdens can be placed on the visual system of an operator of a teleoperator system. For example, the operator usually is constantly monitoring the task visually in order to perform the task and to detect changes in the remote environment which could be hazardous.

Luis deFlorez [1936] conducted a series of experiments that established aural reference axes that could be substituted for visual ones during instrument flying conditions. This enabled the pilot to free his/her eyes from concentrating on instrument indications and to spend more time on other important activities inside and outside of the aircraft. The experiments utilized the binaural sense for directional indication by providing a turn indication consisting of an increase in sound intensity in one ear and a decrease in the other, and having changes in the sound's pitch represent changes in airspeed. The tests were carried out in a Fairchild 22 open-cockpit monoplane with the pilot controlling rudder and elevator only. The aircraft flew a wide climbing spiral, and the blindfolded pilot was able to maintain satisfactory control and even recover from spins. These early experiments proved that aural feedback could be used to substitute for certain characteristics of visual feedback and paved the way for further experiments that would examine different aural indications and the limitations of auditory displays.

Further research in this area conducted by Forbes [1946] at Harvard University in the early to mid 1940's made strides in determining the accuracy and speed of pilot response to a variety of visual and auditory cues. In particular Forbes set out to determine: "(1) what types of auditory signals could be followed with greatest ease, (2) with what accuracy such signals could be utilized, and (3) how many simultaneous auditory signals could be followed successfully." Forbes found that if the signals were properly designed, up to four auditory indications could be followed without hurting overall flying performance.

First, Forbes developed three aural indications that could be followed simultaneously representing turn, bank, and air speed in a Link Trainer. Many types of auditory signals were tested. Combinations of separate tone signals were found to be too complex for the pilots to follow. When using these complex signal combinations it was discovered that subjects would tend to follow only one indication closely and the other two indications would then soon become out of control. In time, two useful auditory signal combinations were developed that successfully represented the behavior of the airplane. The first was similar to the one used by deFlorez, involving apparent motion of the tone to the right or to the left to simulate right or left movement in directional heading combined with a superimposed second indication representing airspeed. The second successful combination involved changing three characteristics of a single signal to indicate turn, bank, and airspeed. The three characteristics for the three-in-one display were a repetitive or sweeping type of motion of the signal from left to right to indicate a change in directional heading, a change in the pitch of the signal to represent a certain tilt or orientation of the airplane, and a "putt" sound that would change its rate of occurrence in association with the sound of the airplane motor to indicate a change in airspeed.

Forbes initially used ten subjects with no previous flying experience to test the effects of the auditory displays on pilot training. The results were comparable to those obtained for the same pilots using visual indicators after the same amount of training time. In addition, six private pilots, some with instrument ratings, were able to operate the Link Trainer successfully with auditory signals after one hour of practice. These results were obtained with the three-in-one display. The first combination display, binaural feedback with a superimposed signal for airspeed, was not as successful when trying to represent three indicators but was equally successful when only two indicators were needed. Further, throughout the testing it was found that simulated radio range signal and voice communication could be heard and understood simultaneously with either display without difficulty. This was due to the fact that tones that would greatly interfere with range and voice signals were not used.

In addition to the tone combinations for auditory feedback, Forbes [1946] also tested automatically produced speech signals generated by an automatic annunciator that announced altitude, airspeed, or other similar instrument indications directly to the pilot. It automatically translated indicator readings into spoken messages and was tested successfully, offering promise of future applications for voice instrument indications and warnings that are present in many of today's aircraft. This seminal work suggested that although auditory displays would probably never entirely displace visual instruments for fundamental aircraft indicators, as many as three auditory signals could indeed be followed with accuracy provided that the aural displays were properly designed. The pioneering work of researchers like deFlorez and Forbes has culminated in the on-going research and development of auditory displays used in today's aircraft that augment the visual displays available to the pilot.

2.1.2 Sensory Substitution with Auditory Mobility Aids

Tachi, Mann, and Rowell [1983] proposed auditory display schemes that communicated the course a blind traveler should follow to comply with information a blind mobility aid acquired. Different display devices were tested that used amplitude modulation to indicate the error of a subject's location from the indicated course. The experimental system measured the location of the human subject and the error was presented to the subject via several alternative amplitude modulation displays: (a) continuous and discrete, (b) toward the sound and away from the sound, and (c) monaural and binaural. The performance of human subjects with various auditory mobility displays was evaluated through transfer function analysis, and an optimal choice for the specific blind person was made based on the results. These experiments demonstrated the feasibility of using auditory displays for blind mobility aids.

2.1.3 Auditory Tracking Displays

Tracking error is usually perceived visually, however representing tracking error through a compensatory tactile or auditory display is also possible. An example of how auditory displays can be designed for tracking tasks is the work of Mirchandani [1971] who conducted experiments to evaluate the use of an auditory display for a dual axis compensatory tracking task. The primary task was the control of an acceleration plant with visual feedback only, and the secondary task was the control of a velocity plant with visual and auditory feedback. The auditory display presented a positive error as an increase in the volume and the pitch, while a negative error was displayed as an increase in volume and a decrease in pitch. The results showed that the secondary task supplemented with the auditory display significantly increased tracking performance, produced more consistent tracking behavior, and increased the human operator gain for the tracking task.

2.2 Tactile Displays

Although most of our everyday environmental sensory feedback comes to us through our vision and auditory systems, the abilities of people who are deaf and blind to understand speech through tactile feedback indicate the potential of the tactile modality as a communication channel. For example, by placing three fingers on the throat, jaw, and lips of a speaker, a properly trained deaf/blind person can understand speech at its normal rate [Bliss, King, Kotovsky, and Crane, 1963].

2.2.1 Tactile Displays for Teleoperated Systems

Bliss, Hill, and Wilber [1971] conducted research with three goals concerning tactile feedback for teleoperator systems: "(1) To improve and extend development of an information processing model of tactile perception by performing experiments on spatial and temporal localization of tactile stimuli. (2) To perform experiments with various forms of tactile feedback from a remote manipulator in an attempt to answer important design questions for a tactile feedback system and to estimate the increase in performance that could be expected with such a system. (3) To experiment with new techniques for tactile stimulation and touch sensing for teleoperators." These researchers studied distributed tactile feedback where the distribution of tactile stimuli on the operator's hand was proportional to the distribution of tactile stimuli on the manipulator. They used a master-slave manipulator, and a tactile display consisting of a 4 X 12 array of piezoelectric vibrators that corresponded to the sensors on the end-effector. Five experiments were conducted, where two were manipulations of blocks and three were manipulations of latches. Their experimental results showed that the success and confidence with which the operator could perform the tasks was much greater with tactile feedback than without. Further, tactile feedback was found to be more beneficial with reduced visual feedback and provided highly useful information that required a relatively low bandwidth channel.

Bliss and Hill [1971] continued to develop tactile displays that could be used for manual and supervisory control. One such system consisted of 21 sensors that were located on the surfaces of the end-effector hand. These sensors were each connected to an airjet tactile stimulator that was mounted on a corresponding area of the operator's hand. A second tactile feedback system was also tested consisting of two 6 X 24 arrays of sensors located on the faces of the end-effector gripper jaw. These sensors were connected to piezoelectric stimulators located on the fleshy pads of the operator's index finger and thumb.

In a study that investigated an operator's ability to track force changes in the grasp of a robotic end-effector, Wiker, Duffie, Yen, and Gale [1990] compared direct force feedback to a simple vibrotactile display. They found that a simple vibrotactile cue, in the absence of bilateral force feedback, was effective in signalling abrupt changes in remote grasp force regardless of magnitude, when changes in force were not too slow. When the operator was required to dynamically track large but slow variations in grasp force, the vibrotactile display was helpful but not as effective as a direct contact force display. Additional insights into these findings are provided in this thesis.

2.2.2 Sensory Substitution Through the Tactile Modality for the Handicapped

Previous research has shown that a vibrotactile stimulus can be used to substitute for visual, auditory, and somatosensory information in persons who are deprived of those sensory modalities. For example, tactile vision substitution was achieved with spatial information gathered by a television camera under the subject's control delivered to the skin through an array of vibratory stimulators or electrodes by Bach-y-Rita, Collins, Saunders, White, and Scadden [1969]. Four hundred solenoid stimulators were arranged in a twenty by twenty array built into a dental chair to vibrate against the skin of the back. The subject manipulated a television camera which scanned objects on a table. After considerable training, blind subjects were able to describe with accuracy the layout of objects on the table, in depth and in correct relationship, even though some of the objects were overlapping and only partially visible.

Further, tactile auditory substitution was developed through a device, Tacticon, that picked up auditory signals by a microphone, divided them into frequency bands, and drove 16 electrodes on an electrotactile belt worn around the waist [Saunders, Hill, and Easley, 1978]. The goal was to teach children who were too deaf to benefit from conventional hearing aids to understand speech sounds which were presented as touch patterns on the abdomen. The aid presented auditory information as flowing, dynamic patterns on the skin, which were learned like a new language.

Thirdly, tactile somatosensory substitution for patients with insensate hands was achieved with a strain gage located in each fingertip of a glove worn on one hand delivering information to the skin of the forehead through five electrotactile stimulators [Bach-y-Rita, 1982]. Within a few hours of training, subjects were able to locate the sensation on the fingertips and to identify various textures. This research was extended to explore the application of this approach to patients with insensate feet due to diabetes, and to space suit gloves for astronauts.

Bliss's work had many spinoff applications including the development of an optical to tactile reader called Optacon (OPtical-to-TActile CONverter) for the blind [Bliss, Katcher, Rogers, and Shepard, 1970; Bliss, 1975; Telesensory Systems, Inc.]. The electronic signal from the Optacon camera read regular inkprint and conveyed information about 144 image points to a processor. The processor then displayed this information through a tactile display that contained an array of 144 vibrating pins driven by piezoelectric crystals. As the blind person moved the miniature camera across a letter, the image was simultaneously reproduced on the tactile array so that the reader felt the image viewed by the camera. It was proven to be useful for reading many types of information that are not easily represented by Braille such as high level college mathematics.

2.2.3 Tactile Tracking

Testing the capabilities of tactile feedback for tracking tasks, Weissenberger and Sheridan [1962] conducted tracking experiments which were analogous to compensatory visual tracking with the cutaneous sense replacing the visual sense. The subjects gripped a spring loaded lever arm with their index finger and thumb and perceived the system error through kinesthetic pressure receptors in their fingertips. The frequency response of the test subjects indicated that tracking performance for a continuous tactile control task, where pressure (error) information is sensed at the same location as the manipulated object is grasped, was similar to that of visual tracking performance. However in a continuous control task, where pressure (error) information is sensed at a location other than where the manipulated object is grasped, i.e. at a finger on the other hand, performance appeared inferior to that described previously as well as to visual tracking.

A pilot flying an aircraft receives position information visually and acceleration information through vestibular feedback. When a ground controller attempts to fly a remote aircraft, he/she has to observe both position and acceleration information visually. This is more difficult and leads to performance which is inferior to that of the flying pilot. Exploring the ability of combinations of visual and tactile feedback to overcome these difficulties, Hirsch and Kadushin [1964] investigated the use of a tactile display that presented an error to come, i.e. the controller would sense the rate of error tactually for a compensatory tracking task while also receiving visual information regarding position error. This provided the ground controller with information warning him/her of a fast build-up of error allowing corrective action. The integration of visual and tactile information in this manner allowed the controller to fly the vehicle "by the tips of his/her fingers" rather than "by the seat of his/her pants."

Hirsch and Kadushin performed qualitative two-axis tracking experiments using an airplane stick on top of which a spherical handle was mounted with four vibration transducers on the sphere surface. The operator would receive a buzz from a certain transducer which informed him/her to move the stick in the direction indicated by that transducer until the signal stopped. An oscilloscope provided visual feedback when finer control was necessary. Results showed that subjects could accurately balance either longitudinal or lateral deviations separately without visual feedback, but needed visual feedback when longitudinal and lateral deviations were presented simultaneously. Therefore they decided to perform their quantitative testing with a single axis compensatory tracking task. During these experiments, the visual display showed position error, and the tactile display presented error rate. The tactile stimuli were transferred to the controller through two small vibratory transducers situated on the control stick and stimulating the controller's fingernails. The vibrations indicated a rate of error greater than a threshold level to the controller. The experimental results showed that visual information combined with tactile information produced a significant improvement in performance over the visual only situation, by reducing error and increasing the ground controller's precision in flying the vehicle.

Bliss [1967] performed tracking experiments to try to quantify human operator describing functions when using tactile displays as compared to those with visual display. The Bode plots of each case showed that amplitude differences were significant but the phase curves were practically identical. Thus Bliss concluded that tactile performance had equal bandwidth, but less gain, than performance with visual displays. Bliss, Hill, and Wilber [1969] performed a series of experiments that further investigated various characteristics of tactile information processing. These researchers modeled the information processing characteristics of the tactile channel as shown in figure 1.

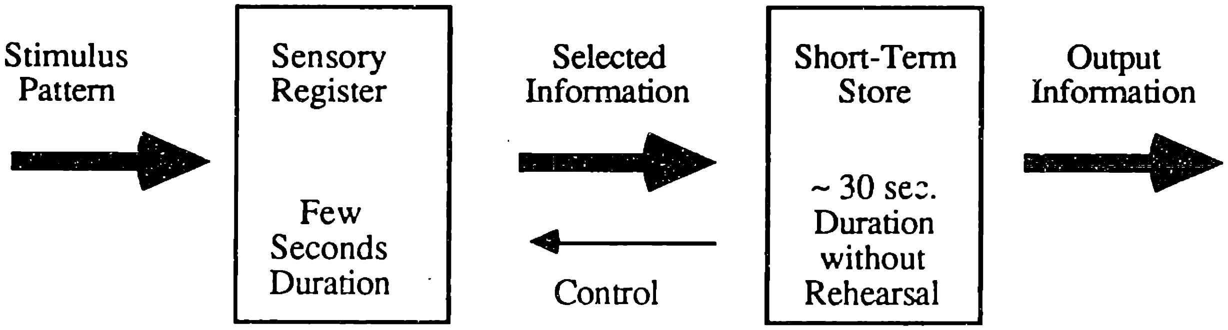

Figure 1 - Framework for the Memory-System Model.
From [Bliss, Hill, and Wilber, 1969], p. 161.

According to their model, when a tactile pattern is presented to the somatosensory receptors a filtered image of the pattern is transferred to a sensory register where it begins to decay exponentially with a time constant of 1.4 seconds. The capacity of the sensory register is limited by spatial resolution, and localization errors tend to be in preferred directions near the point of stimulation. As the image in the sensory register decays, a portion of this information is processed and transferred to a short-term storage area whose storage capacity is at least fifty percent less than the sensory register. This was the first model to describe both the spatial and temporal limitations and capabilities of the somatosensory system in processing tactile feedback information. Their preliminary research measured pilot describing functions with several types of tactile displays and found performance to be comparable to that with peripheral vision.

2.3 Sensory Substitution in Physical Rehabilitation

Sensory substitution has also been used in rehabilitation engineering in order to help convey head, trunk, or limb position and muscle contraction information to the patient [Bach-y-Rita, 1982]. Brudny et al. [1976] provided electromyographic (EMG) feedback to patients with abnormal neuromotor control by displaying the degree and rate of muscle contraction on an oscilloscope. In addition, an auditory display was used that presented the change in EMG activity as changes in click rate or intensity of a tone. These sensory substitution techniques improved the patients' sensorimotor interaction and accuracy of voluntary movements.

Providing sensory information from an artificial limb has also been a major research area for sensory substitution in rehabilitation. For control of upper-extremity prostheses, shoulder position provides some kinesthetic feedback, but vision provides most of the position information on the forearm which can limit use of the prosthesis to the field of view [Bach-y-Rita, 1982]. Using sensory substitution to present kinesthetic information, Alles [1968] utilized two tactile stimulators on the upper arm to indicate the joint angle of an artificial elbow. As the amputee flexed his/her elbow, the location of the tactile sensation was varied by changing the relative amplitude or temporal patterns of stimulation at each stimulator thus causing the sensation to travel along the arm. Alles [1970] also found that learning how to use the display was easy and required no formal instruction. Although the display had less transmission capability than natural physiological feedback, for motions of moderate speed and for positioning the sensory substitution display appeared accurate enough to be useful to an amputee. Further examining the use of this cutaneous display of elbow angle to help an amputee position a prosthesis, Mann and Reimers [1970] found that when sound was occluded, using the tactile feedback display developed by Alles [1970] reduced positioning errors by 50 percent. In another study aimed at helping the training process of above-knee amputees with their prosthesis, Cullen [1984] used biofeedback to present information on prosthetic weight bearing. An auditory cue was the preferred feedback presentation and enhanced the learning of some amputees.

2.4 Sensory Substitution of Force Feedback through the Visual Modality

Sensory substitution of force feedback through the visual modality has been studied at JPL with some success. Bejczy and Handlykken [1981] found that a quantified graphic display of force-torque information considerable aided the operator in performing a quantitatively sharp force-torque control through a bilateral force-reflecting control system.

However, further research has pointed to the limitations of visual force-torque displays. Bejczy, Dotson, Brown, and Lewis [1982] tested a sensor-claw-display system with the simulated full-scale Space Shuttle Remote Manipulator System (RMS). The system provided data on the three orthogonal forces and three orthogonal torques acting at the base of the manipulator claw and displayed them to the operator on a graphics display. When performing payload berthing tests, average task completion time was fastest when using the force-torque sensor display only as feedback, and slower when using a visual view of the task alone. However when the force-torque graphic display was used in conjunction with a visual view of the task, task performance was slowest. This led them to conclude that simultaneous visual feedback of the scene and of force feedback could lead to longer performance time due to difficulty in properly coordinating information which led to excessive operator perceptive workload.

2.5 Processing of Bisensory Information

Much of the information presented in this section was used not only for background knowledge, but also to assist in analyzing the experimental results. References to some of the studies in this section are made during the analyses presented in chapters 9 and 10.

Using a vibrotactile display or an auditory display to present force information in conjunction with a visual display of the remote task produces a bisensory feedback scenario, i.e., the operator receives information from two senses concurrently. When considering the use of bisensory displays, an understanding of the human operator's ability to process bisensory information becomes important. Since the human operator can become confused, disoriented, and unable to perform efficiently when he/she is required to attend to a number of stimuli simultaneously, it is important to understand how this information can be processed in order to determine potential benefits and dangers of bisensory feedback.

Much research has been devoted to examining this issue and to developing models of human information processing when receiving sensory input from multiple sources and modalities. Particular attention has been given to modeling the human operator as a single- or multiple-channel processor. The overall conclusion is that a human operator can attend to simultaneous stimuli and successfully perform a task given that the information is presented clearly and at an appropriate transmission rate. However the actual mechanism by which this is accomplished is disputed and several different theories are proposed.

2.5.1 Models of Bisensory Information Processing

Oatman [1975] observed that research on the processing of bisensory information could be classified into two broad categories. One is the accessory stimulation category which includes those studies where the stimulation to one modality is regarded as relevant while stimulation to the second is irrelevant but may affect the subjects' response. The results of research in this area have not come to a single uniform conclusion and instead have shown that accessory stimulation can have facilitating effects, inhibiting effects, or no effects. Second, the functional stimulation category includes research where both sensory modalities are conveying relevant information. This category can be broken down even further into presentation of redundant and non-redundant information. A further breakdown can be made into information that is functionally identical or different. Mowbray and Gebhard [1961] showed that with functionally different stimuli, there has been a failure to show that efficient divided attention is possible without rapid alternation of attention or similar strategies which may minimize information loss.

Broadbent [1958] hypothesized that human operators act as single channel processors with a peripheral filter that blocks out all but one selected input as is shown in figure 2.

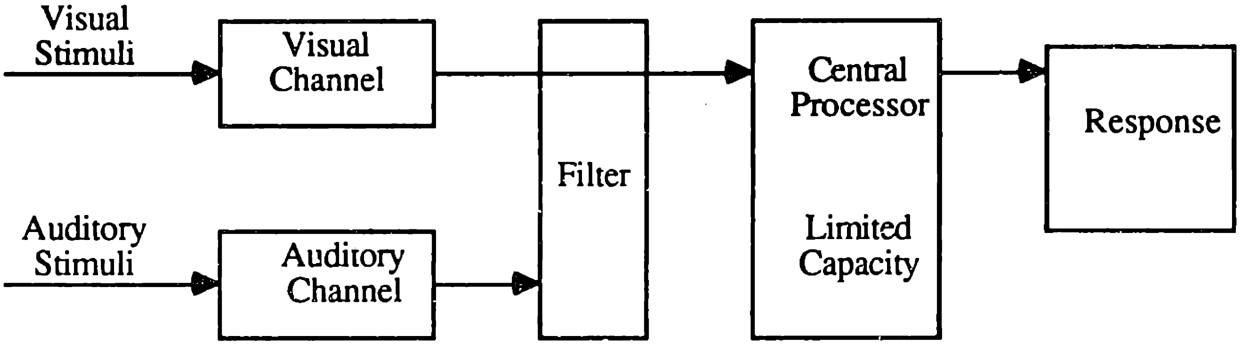

Figure 2 - Broadbent's Single Channel Processing Model.
From [Oatman, 1976], p. 5.

The filter in figure 2 would make its selection based on physical cues such as spatial location, voice, intensity, etc. Once the input channel was selected the input would have access to long-term memory storage and response mechanisms. To process simultaneous multiple inputs, the human switches from channel to channel, sampling information for a brief, finite interval from each channel in turn. A short term storage is postulated to exist in order to counteract the effects of a limited central processing mechanism and time wasted during switching. This short term storage can briefly hold information received from one modality while information arriving from another modality is processed.

In experiments conducted by Halpern [1971] on redundant and nonredundant presentation of information across modalities, it was concluded that Broadbent's filter theory provided the best description of the research data. If one assumes a single-channel model, it would seem unlikely that redundant information presented to two modalities would increase operator performance since one item of information must be processed before another item can enter the processing system [Oatman, 1975]. A possible exception to this single channel effect would occur if the information rate is slow so that the operator can switch from channel to channel without losing data. At high transmissions rates, switching between modalities would lead to a decrease in performance. Broadbent concluded that only when lossless alternation between channels were possible would there be an increase in performance with the presentation of unrelated information to two modalities.

In contradiction to the single channel theory, Treisman [1960] found that subjects also would respond to input from secondary channels, indicating that information could flow through a number of parallel channels. Treisman concluded that the filter merely attenuates input from secondary channels rather than blocking it. The information would be analyzed by the nervous system for physical properties such as loudness, pitch, position, color, brightness, etc. Thus the central nervous system could be thought of as a filter that attenuates information from one sensory system when it is necessary to pay attention to information coming in from another sensory system [Oatman, 1976].

Deutsch and Deutsch [1963] suggested that it was unnecessary to describe bisensory information processing with any type of filter. They proposed that all messages receive the same information processing regardless of whether or not they are paid attention to as displayed in figure 3.

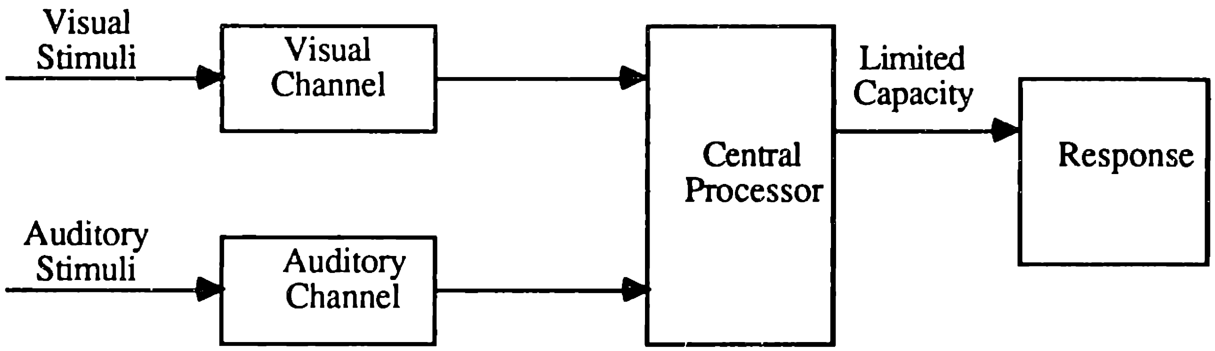

Figure 3 - Model of Bisensory Information Processing Developed by Deutsch and Deutsch. From [Oatman, 1976], p. 10.

All of these theories suggest that in order to perform efficiently an operator must somehow be able to filter out irrelevant information and pay attention to what is necessary to do the job. It is generally agreed upon that the human operator has a limited capacity to receive, process, store and act upon information, so that some sort of selective process must exist within the CNS which causes relevant sensory information to be perceived, while irrelevant information is rejected. Thus a theory of selective attention has been proposed to describe the interactions between auditory and visual information processing.

Oatman [1976] tried to tie these and seemingly countless other theories into a generally accepted model suggesting that a central processor allocates capacity for processing certain sensory messages in preference to others. This model is shown in figure 4.

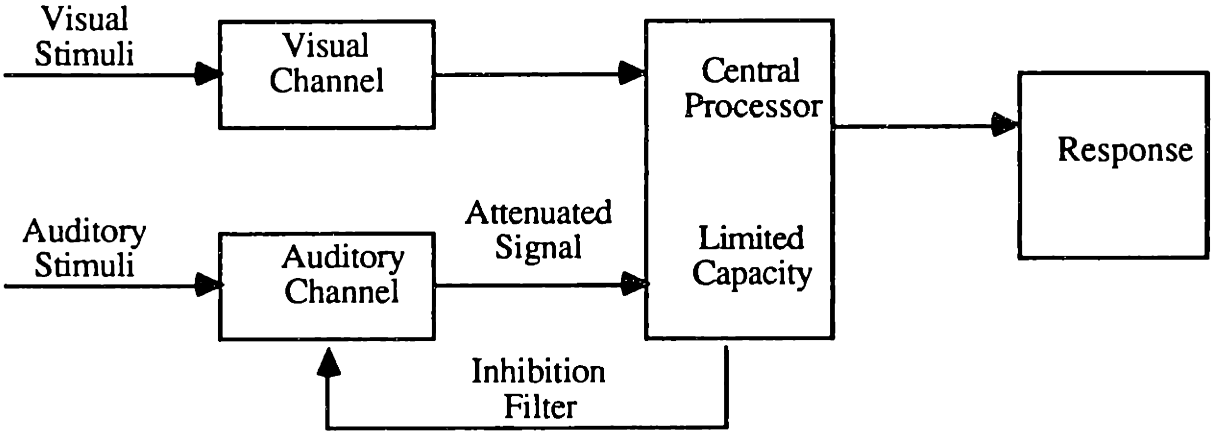

Figure 4 - Single Channel Information Processing Described by Oatman.
From [Oatman, 1976], p. 10.

Figure 4 displays a model that is effectively a single channel model of information processing containing a peripheral filter that attenuates some sensory information. This protects a central processor of limited capacity from overload by simultaneous stimuli. The central processor can activate an inhibitory system which in turn attenuates sensory information at the peripheral receptor level. An appropriate response is then elicited by the central processor and executed by the selected output mechanisms. Oatman advised that the focusing of attention is very effective in attenuating irrelevant stimuli and keeping irrelevant stimuli from interfering with the primary tasks, but that this does not prevent irrelevant stimuli from being processed especially at the lower processing levels. Rejecting irrelevant stimuli also is dependent upon the amount of capacity the primary task demands. Oatman's model helps one to understand how the human operator can routinely operate in an environment where many signals compete for attention, where the time available for dealing with each signal is limited, and where the precision of analysis required is continuously changing.

2.5.2 Effects of Training on Bisensory Information Processing

Researchers have also found that when subjects were required to attend to simultaneous auditory and visual sources of stimuli and to integrate information across channels, there were found to be initial difficulties that were overcome with practice [Oatman, 1976]. Halpern [1970] also discovered that learning affected his research results. He found that there was no significant benefit with bisensory feedback over unisensory feedback over the first 320 trials for a signal detection experiment with untrained subjects. However on the second 320 trials, bisensory feedback, (using both auditory and visual cues) was clearly superior. It appeared that subjects with unisensory conditions learned all they could about the task earlier and did not reach performance levels attained by those presented with bisensory feedback. Thus learning and training are key in developing models of bisensory information processing and obtaining the true value of bisensory feedback.

2.5.3 Sensory Dominance

In many human perception situations, visual input can take precedence over input from other modalities [Posner, Nissen, and Klein, 1976]. For example, Gibson [1933] showed that vision can dominate the tactile modality by having subjects wear prism goggles which made straight edges appear curved. While the subjects moved their hands along a straight edge, they watched through the goggles concurrently. Due to the dominance of visual input, the subjects experienced no conflict and responded that the edge felt curved despite the presence of the tactile input that detected the straight edge. In another study, Pick, Warren, and Hay [1969] demonstrated visual dominance over proprioception during perceived object location tasks, by reporting that subjects wearing prism goggles more frequently determined position based on visual information rather than the position actually felt by the hand.

Vision has also been noticed to dominate audition. Pick, Warren, and Hay [1969] had subjects wearing prism goggles point to the perceived location of the source of a stimulus under four conditions: 1) a displaced visual target (a speaker emitting no sound), 2) an auditory source with vision obstructed, 3) the "heard" position of a sound with a speaker in view, and 4) the "seen" position of speaker emitting sounds. Their results indicated that vision significantly biased auditory judgements, whereas audition did not at all bias visual directional judgements. Colavita [1974] presented visual and auditory signals as cues for reaction time tasks. When visual and auditory stimuli were presented simultaneously, subjects responses were dominated by the visual stimulus. Further, on some occasions, subjects were unaware that the auditory stimulus was presented.

2.5.4 Bisensory Performance

As tasks become increasingly difficult due to the stimulus signals becoming more difficult to detect, recognize, or discriminate, presentation of the information over more than one sensory modality has been observed to improve performance [Oatman, 1975]. If the presentation of information is clear and relatively easy to interpret, performance results for redundant information over two sensory modalities has been found in some studies to be equal to results obtained when using only the modality which is superior in single-modality comparisons. For example, Hershenson [1962] found in reaction time studies with vision and audition that when the signals were presented simultaneously or when there was a small precedence of the visual signal, the reaction time was equal to reaction time of using the auditory signal alone due to the shorter auditory reaction time versus visual reaction time.

However, redundant presentation has also been shown to impede performance. Reaction time is quicker to a proprioceptive displacement cue than to a visual displacement cue when each is presented independently. However, Jordan [1972] found that when both cues were presented concurrently, reaction time increased beyond that for proprioception alone. These results are similar to those of Colavita [1974] cited earlier, and can possibly be explained by the effects of visual dominance with visual information attracting the subject's attention and slowing down reaction time.

Performance degradations can also occur .f the presentation of the bisensory data is not properly designed and implemented. Hartman [1961] found that interference among information simultaneously presented by auditory and visual channels may occur when the information is presented in a format requiring a high cognitive difficulty or at a rate of presentation such that successful alternation of attention between channels is not possible. If one of the displays demands too large an amount of attention, interference will result and task success will be in jeopardy [Adams and Chambers, 1962]. Presenting separate, unrelated information to several modalities compels the operator to switch attention between channels. As the information becomes more difficult or complex, the operator will have increasing difficulty with this switching and as a result ignore one channel and focus his/her attention on only input [Oatman, 1975]. The displays used in this thesis have been designed to be easy and natural to interpret. Attempts were made to not overload either sensory modality, and to not divide attention away from the visual modality.

3. EXPERIMENTAL TESTBED

A testbed for experimentation on the use of auditory and vibrotactile displays for sensory substitution of force feedback during teleoperation was developed. This chapter provides descriptions of the force sensing resistors, auditory display, vibrotactile display, master-slave manipulator, and visual system which made up the testbed. The tasks boards designed for the experiments are described in the respective chapters on experimentation.

3.1 Design Overview of Sensors and Displays

An overview of the design of the sensor-display system is shown in figure 5. The experimenter chose between two options: 1) auditory display with a change in loudness of a tone representing a change in force, and 2) vibrotactile display with a change in the amplitude of the vibrotactile stimulation representing a change in force. The choice was input to an AT&T 6300 Personal Computer. A Data Translation DT-2801 input-output (I/O) board with sixteen analog to digital (A/D) channels and two digital to analog (D/A) channels, and a Data Translation DT-2816 output board with four additional D/A channels were placed inside of the PC. The number of A/D channels used for a given experimental test corresponded to the number of force sensors needed for the task. The force sensors were force sensing resistors (fsr's) made by Interlink Electronics. For the experiments which are described later in this thesis, the number of fsr's used ranged from two to nine. Based on the choice made by the experimenter, the appropriate display option was invoked. To stimulate the headphones which presented the auditory stimuli to the operator, a Creative Music System (C/MS) audio card made by Creative Labs, Inc. was used. For vibrotactile force presentation, the D/A channels on the DT-2801 and DT-2816 boards were used to stimulate two to five vibrators that presented the vibrotactile stimuli. The original vibrotactile display electronics unit was developed by Patrick [1990], and contained two

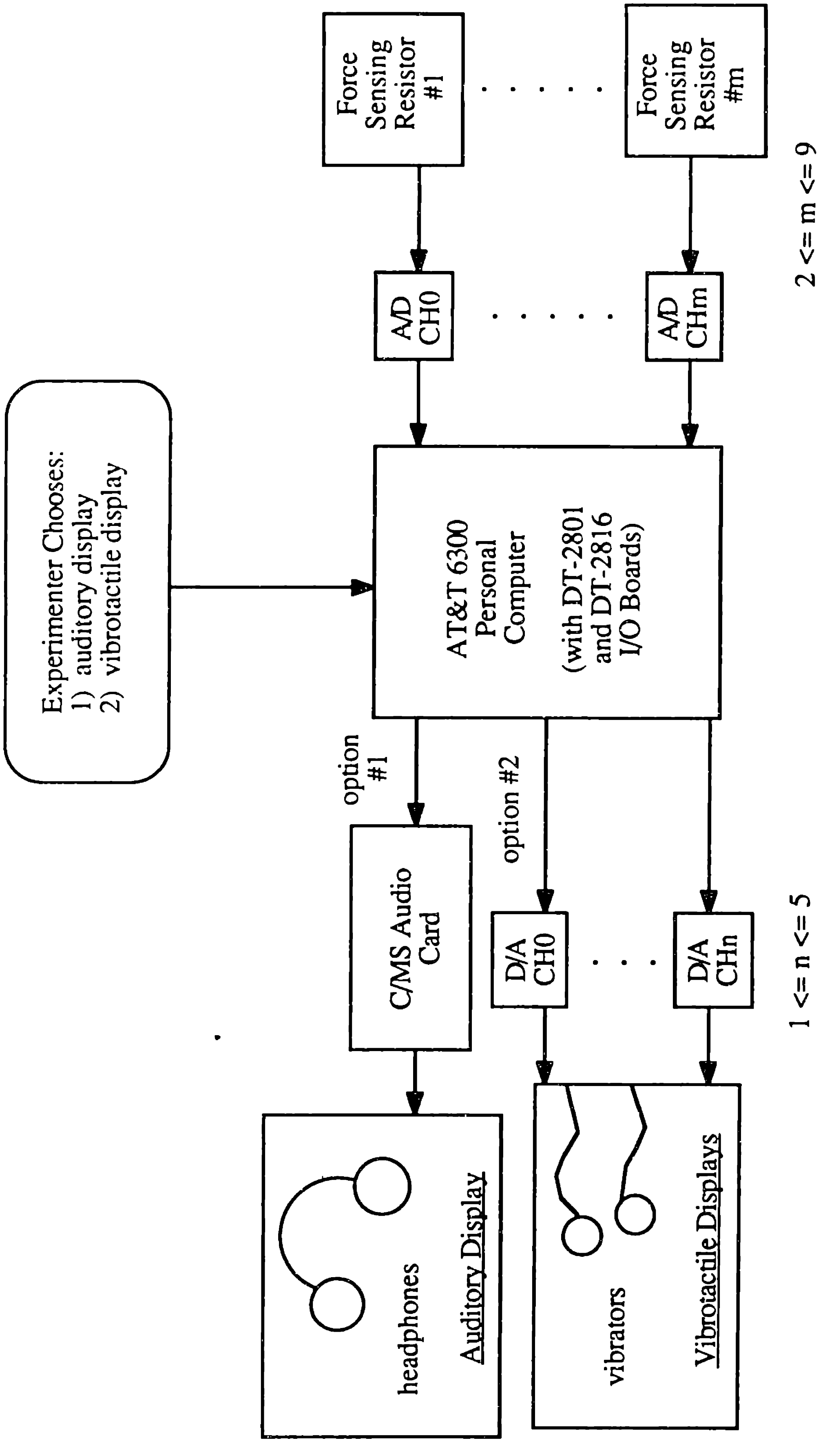

Figure 5 - Sensor-Display System Overview

vibrotactile displays. An additional display electronics unit was built based on Patrick's design, and contained three vibrotactile displays to accommodate all of the experiments.

3.2 Force Sensing Resistor (fsr)

The force sensors used for this testbed were Force Sensing Resistors (fsr) made by Interlink Electronics in Santa Barbara, CA. The fsr is a polymer thick film device which exhibits a decreasing resistance with increasing force applied normal to the device surface [Interlink Electronics, 1989a]. A basic fsr has two polymer sheets laminated together: one sheet is coated with interdigitating electrodes, the other sheet is coated with proprietary semiconductive material. When a force is applied to the fsr the semiconductive material shunts the interdigitating electrodes causing the resistance to drop [Interlink Electronics, 1989b]. Fsr's come in a variety of shapes and sizes. A drawing of a typical fsr (not to scale) is shown in Figure 6.

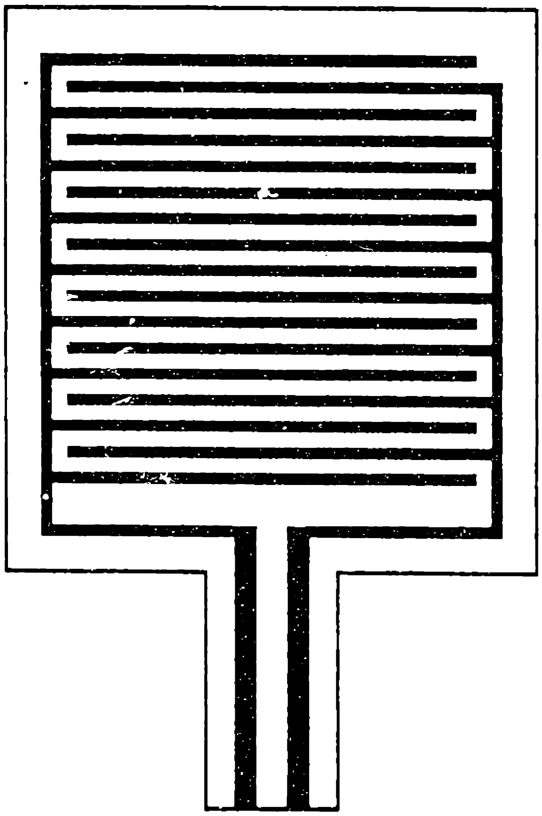

Figure 6 - FSR
(Source: [Interlink Electronics ,1990])

3.2.1 Calibration

The force sensing resistors were calibrated by applying different forces (weights in pounds) to the fsr surface and measuring the associated resistance (in ohms) output from the fsr. A thin piece of rubber was placed over the active area on the top surface of the fsr to better distribute the load across the fsr, allowing more accurate force readings. The active area is just within the outer border of the device and is black. The fsr was mounted to a piece of plastic that corresponded to the active area. This further ensured that the entire active area would be stimulated by an applied force. A calibration platform was built with a smaller lower half that fit within the fsr active area, and a larger upper half that allowed weights to be applied to the fsr. The calibration setup is shown in figure 7.

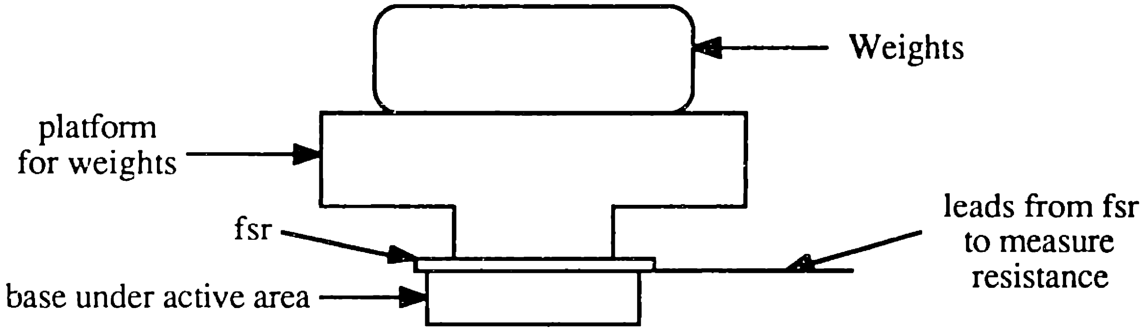

Figure 7 - Fsr Calibration Setup

The results of the calibration for a typical fsr is shown as a resistance versus force curve in figure 8.

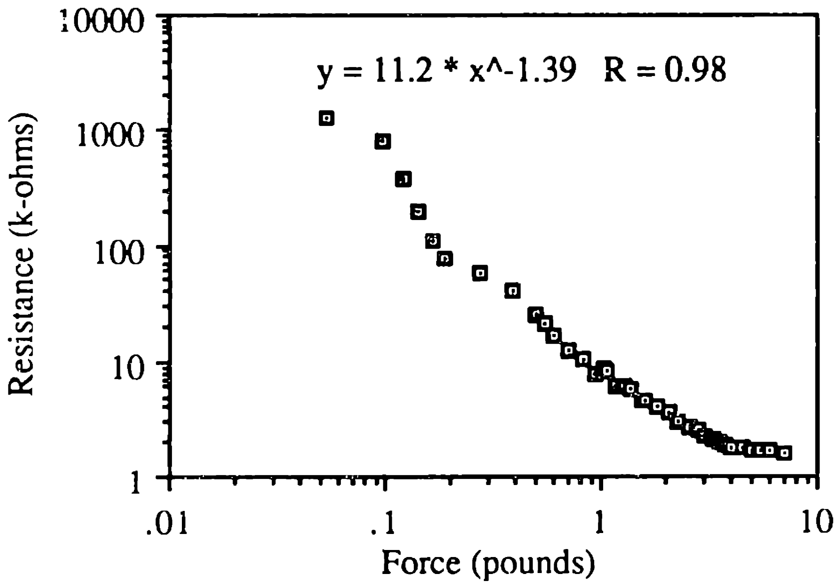

Figure 8 - Resistance vs. Force Characteristic for a Typical FSR

3.2.2 FSR Circuit

A circuit was designed to read each fsr based on the fsr's resistance vs. force characteristics. The objective was to build circuits that would output ranges of voltages to represent force ranges from zero pounds to the maximum force in each translational degree of freedom that could be exerted by the E-2 manipulator in the Man-Machine Systems Laboratory. The E2 was the manipulator used in experiments with this testbed. For the y-direction (forward and backward motion) the maximum possible applied force was approximately ten pounds, for the x-direction (side to side) and the z-direction (up and down) the maximum applied force was approximately five pounds. The current through the fsr was suggested by the manufacturer to be limited to approximately 1 to 2 mA. A typical circuit is shown in figure 9. One such circuit was required for each fsr and the magnitudes of the components used were based on the characteristics of the associated fsr.

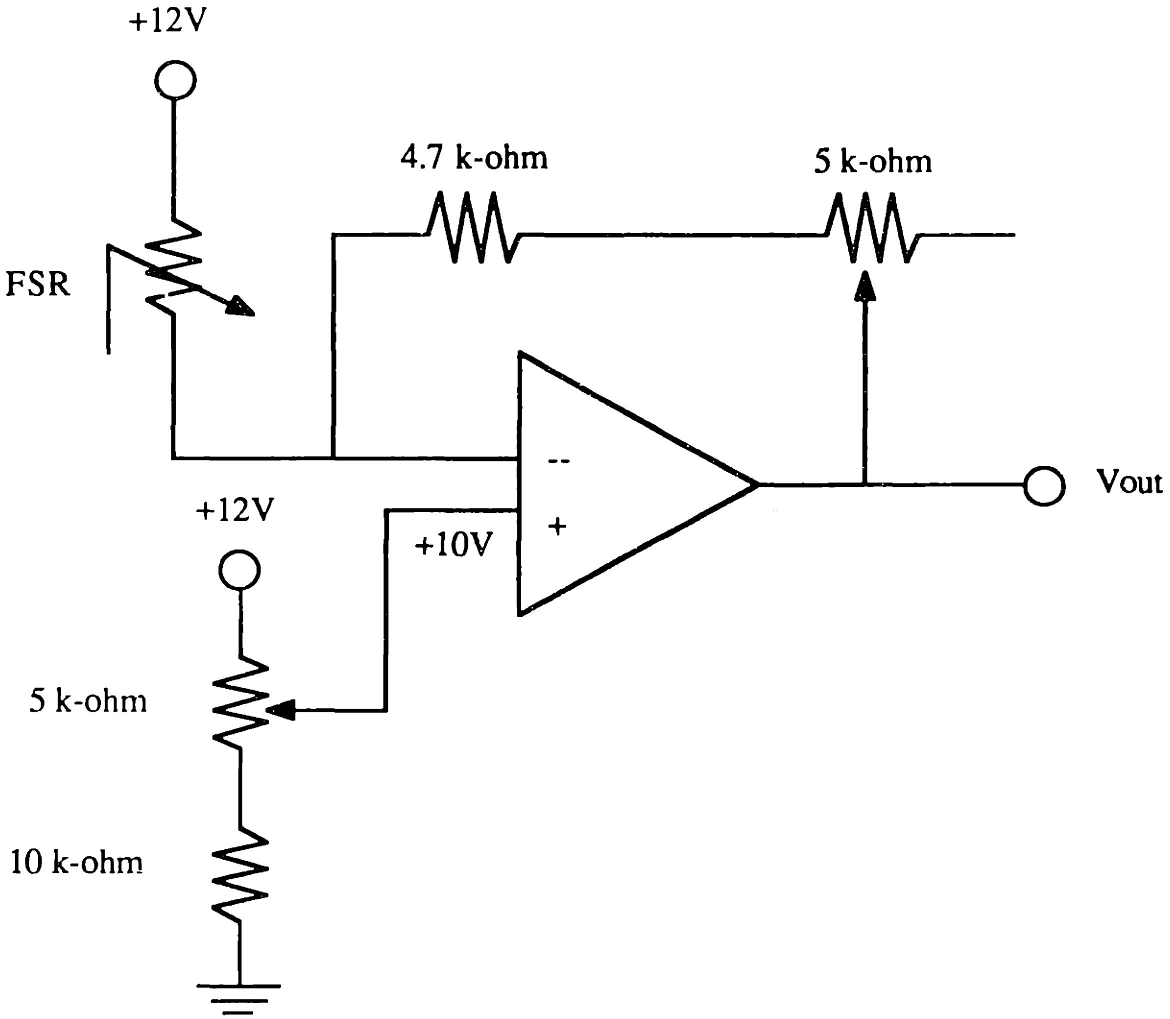

Figure 9 - FSR Circuit

The power supply had +12 volts, -12 volts and ground terminals. The bottom left portion of figure 9 served as a +10 volt power source to the positive input terminal of the op-amp. To accomplish this a 10 k-ohm resistor was attached to ground and placed in series with a 0-5 k-ohm trim-potentiometer (trim-pot). The +12 volt source was attached to the other end of the trim-pot. The voltage into the op-amp was measured from ground up to the trim-pot, and the trim-pot was adjusted until the voltage was exactly 10 volts.

The properties of op-amps dictated that the voltage at the negative terminal was + 10 V since the voltage at the positive terminal was set to be + 10 V. The voltage across the fsr was then 2 V. The resistance of each fsr ranged from over 1 M-ohm at zero force to a smaller resistance at maximum force. For the fsr described in figure 8, the minimum resistance was approximately 1500 ohms at five pounds of force. Thus the current through the fsr ranged from approximately 0 at zero force to approximately 1.3 mA at high force which was within the suggested range for fsr current.

For fsr described by figure 8, having a 4.7 k-ohm resistor in series with a 0-5 k-ohm trim-pot as shown in the upper part of the circuit diagram, allowed voltage swings from 10 V when no force was present to 0 V when a five pound force was present. These resistance and trim pot magnitudes were dependent on the characteristics of each individual fsr. The voltage equation for the upper portion of the circuit was 12 V = Vfsr + V1 + V2 + Vout, where Vfsr was the voltage across the fsr which equals 2 V, V1 was the voltage across the 4.7 k-ohm resistor, V2 was the voltage across the portion of the pot which was connected to the 4.7 k-ohm resistor, and Vout was the op-amp output voltage which corresponds to the voltage across the portion of the trim-pot not connected in series with the 4.7 k-ohm resistor. The equation then cancels to V1 + V2 + Vout = 10V. Since an op-amp draws no current, the current through the resistors equaled (Vfsr/Rfsr) = (2V/Rfsr), where Rfsr is the resistance of the fsr measured at any particular time. Now the equation was Vout = 10V - (4.7 k-ohm)(2V/Rfsr) - (R2)(2V/Rfsr). When there was no force at the fsr, Rfsr was be huge and Vout equaled ten volts. The correct value to which the trim-pot was adjusted depended upon the characteristics of the particular fsr. The fsr resistance value at maximum force was substituted for Rfsr and Vout was set to be zero. The trim-pot was tuned to insure that Vout would be zero volts at maximum force, giving a swing of 10 V to 0 V for changes in force from 0 pounds to maximum force. For example, if Rfsr was 1400 k-ohm at maximum force, the trim-pot resistance in series with the 4.7 k-ohm resistor was set to approximately 2.3 k-ohm, giving a Vout of zero at maximum force. The relationship between output voltage and applied force for the fsr described in figure 8 is shown in figure 10.

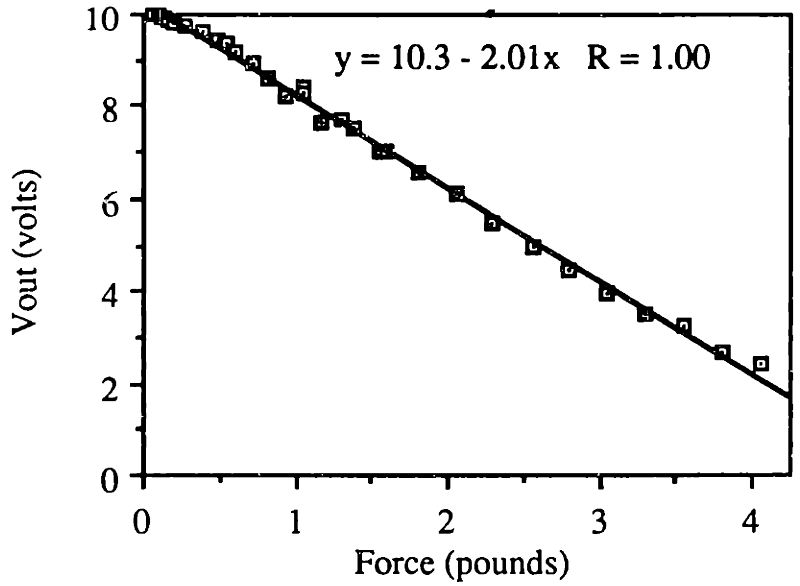

Figure 10 - Voltage vs. Force Characteristics for a Typical FSR

The output voltages from each op-amp were sent over the appropriate A/D channel and delivered to the software to provide a measure of the forces present at each fsr.

3.2.3 FSR Software

A function called fsr_in() was written to read the force on each fsr. Figure 11 shows a block diagram of the fsr software. After the function was called, the A/D channels were read, A/D units were converted to voltage, and the force was determined by the voltage to force relations derived from relationships such as the one displayed in figure 10.

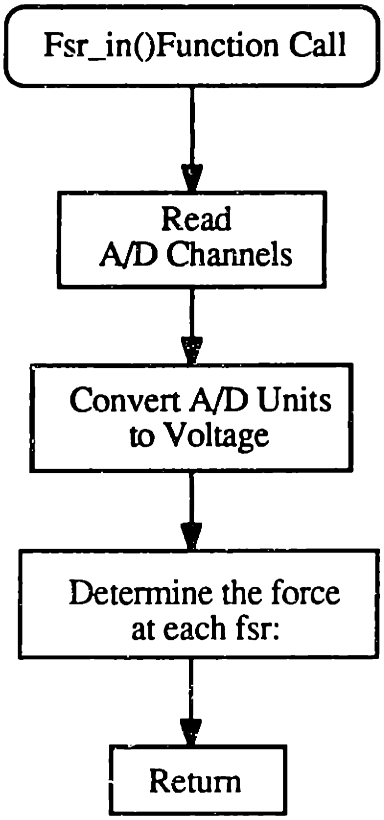

Figure 11 - Fsr Software

3.3 Auditory Display

The auditory display consisted of a set of stereo headphones that were controlled from a C/MS PC music card made by Creative Labs, Inc. The card can be used to independently control up to 12 different audio signals. Each signal had a single square wave frequency. The card had 4 bits for amplitude control of the right channel (right ear) and 4 bits for amplitude control of the left channel (left ear) for each of the 12 tones. This enabled stereo presentation. There were also eight bits for frequency control of each of the 12 tones, and 3 bits for octave control. The frequency and octave ranges produced a frequency range from 20 to 7000 Hz. This range contained the frequencies at which the human ear is most sensitive and the fundamental frequencies that correspond to all of the notes on a piano keyboard (see figure 12). The capabilities of the board allowed a change in force at any of the fsr's to be presented to the subject with frequency and location of the tone identifying the position of the force, and with amplitude (loudness) of the tone representing the magnitude of the force.

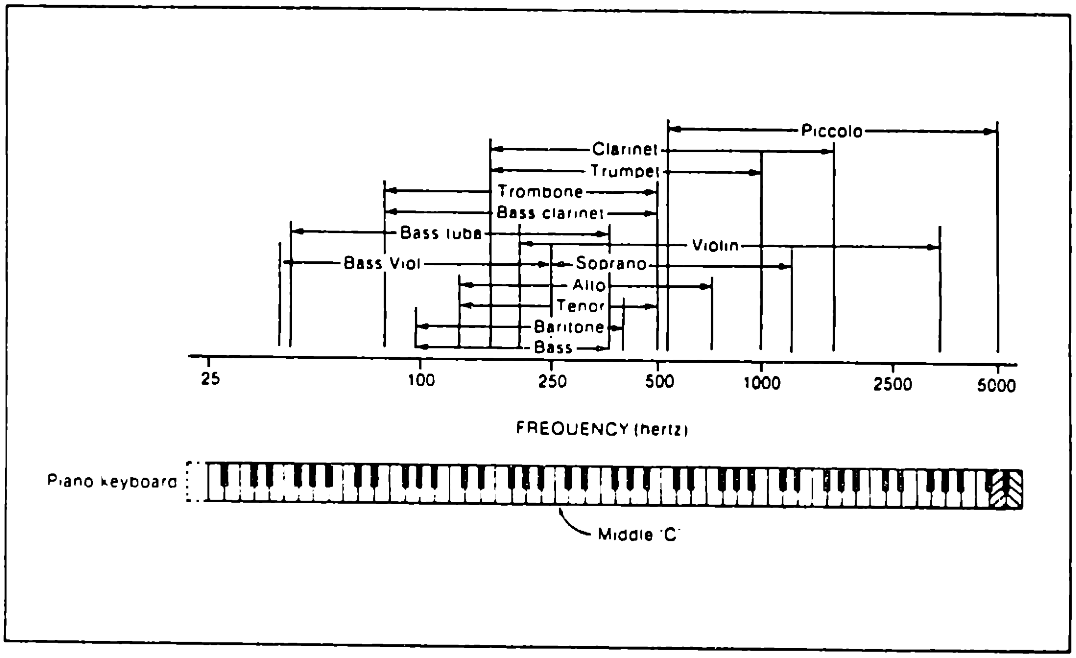

Figure 12 - Range of fundamental frequencies produced by musical instruments and singing voices. (Source: [Scharf and Buus, 1986])

3.3.1 Loudness vs. Intensity

Intensity is a physical property of sound (the rate of energy transfer), whereas loudness is a subjective psychophysical property. Loudness is the sensation magnitude or perceived perceived intensity of a sound, and it increases with sound intensity [Boff and Lincoln, 1988]. Changes in loudness make perceptual differences to humans, and the design of the auditory loudness display included the determination of a relationship to represent a change in force as a change in loudness.

Several experimental studies have been conducted to determine how loudness depends on stimulus intensity or level. Most of these studies were conducted with a 1,000

Hz tone, since this is the frequency at which the ears have the lowest threshold when earphones are worn [Scharf and Buus, 1986]. For these reasons, a 1000 Hz tone was selected to represent forces whenever practical during the psychophysical and teleoperation experiments described later. The data in figure 13 show the relationship between loudness and sound pressure level in decibels [Scharf and Houtsma, 1986].

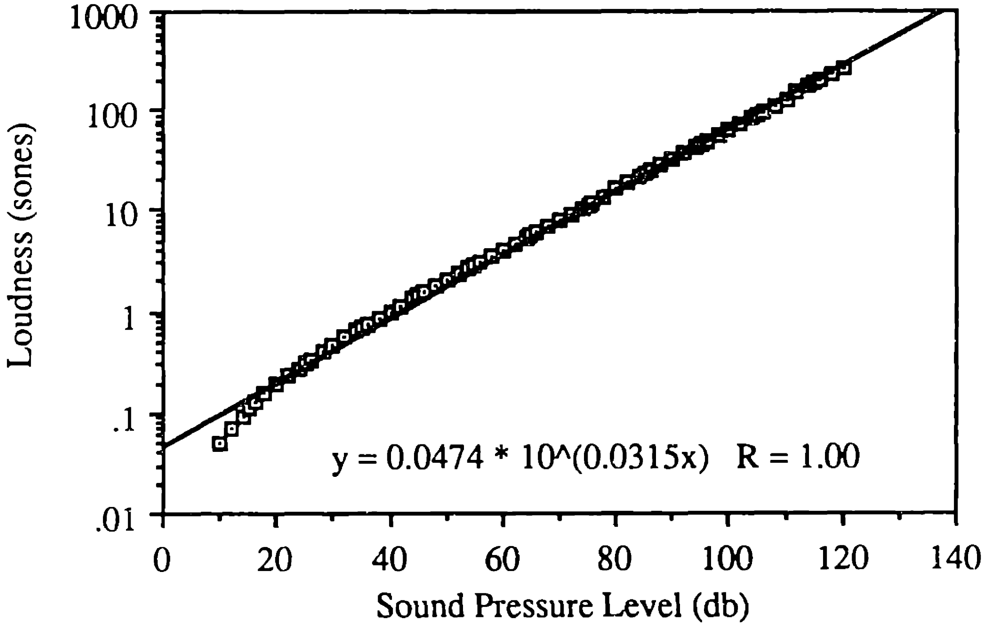

Figure 13 - Loudness vs. Sound Pressure Level

The headphones used were small stereo earplugs from Radio Shack that fit snugly in the subjects' ears, and had a frequency response range of 16-22,000 Hz. The subjects wore a pair of industrial Bilsom ear muffs, made by the Viking Corporation, on top of the earplugs to cut down on environmental noise and increase the efficiency of the auditory stimulus. A test subject wearing the auditory display while controlling the E2 manipulator is shown in figure 14. The C/MS card had 4 bits for loudness control through the loudness control register. Therefore the input value to the loudness control register ranged from 0 to 15 in decimal units, where 0 corresponded to zero loudness and 15 corresponded to maximum loudness. The auditory display was calibrated with the C/MS card, and the

Figure 14 - Test Subject Wearing Auditory Display

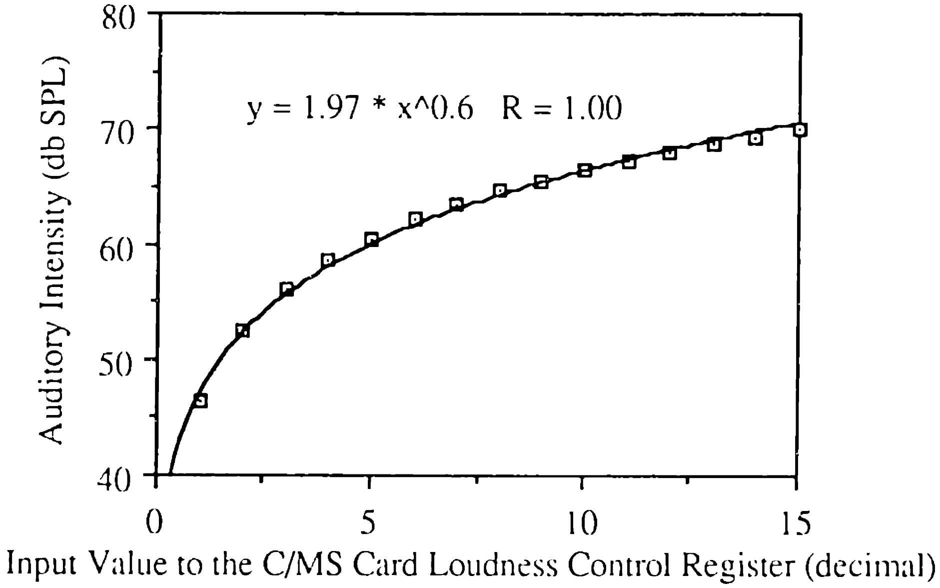

Figure 15 - Calibration Results for the Auditory Display

relationship between the input value for the loudness control register in decimal units for the C/MS card and the corresponding db SPL output from the ear plugs is shown in figure 15.

3.3.2 Representing Force as a Change in Loudness

Figure 13 summarized measurements taken from the standard of the International Standards Organization. Sound pressure level in db was related to sound pressure in micropascals by the following formula: number of db = 20 * log (P/20), where P is sound pressure in micropascals. Converting sound pressure level in figure 13 to sound pressure in micropascals gave L = k * (P ^ 0.6), where L is loudness in sones, k = 0.01, and P is the sound pressure in micropascals. The sone was arbitrarily scaled and is defined as "a unit of loudness such that a 1,000 Hz tone heard binaurally at 40 db has a loudness of one sone." [Scharf and Houtsma, 1986]

The C/MS board had 4 bits for volume control, i.e., 16 different levels for the volume register value. Further, sound pressure from the board was linearly proportional to the volume register value. Therefore volume register value was substituted for sound pressure, P, in the above mentioned equation and allowed to vary between 0 and 15. Further, loudness in sones was linearly scaled to force between 0 and 5 pounds for x and z translation forces and from 0 to 10 pounds for y translation forces. This produced an equation of F = k * (VRV ^ 0.6) where F is the force in pounds, VRV is the volume register value in decimal numbers, and k is a constant to be determined and dependent on the force range. By letting zero force be represented by zero volume register value and five or ten pound forces (depending on the degree of freedom) be represented by a volume register value of 15, k was estimated at 0.95 for 0 to 5 pounds and at 1.97 for 0 to 10 pounds. These functions are shown in figures 16 and 17 and relate changes in the volume register value of the C/MS board, i.e., a change in sound pressure, to a change in the perceived force by varying the perceived loudness of the tone.

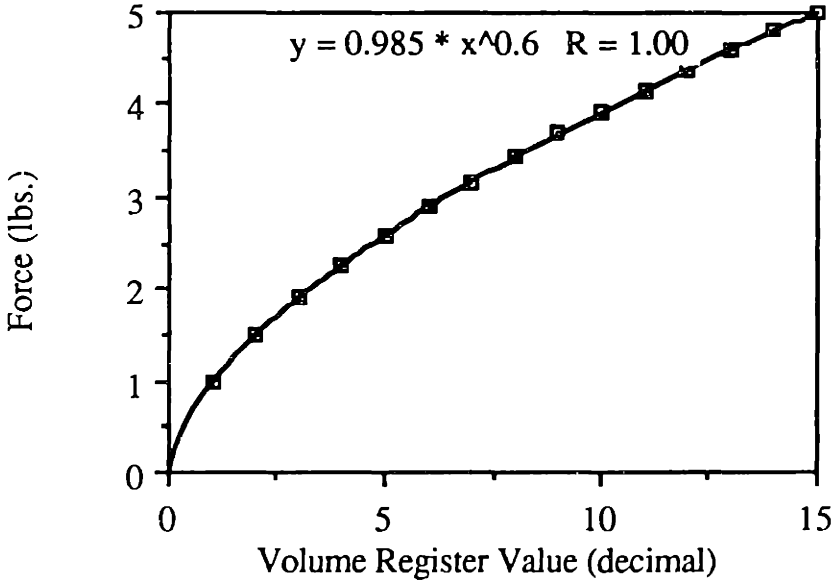

Figure 16 - Force vs. Volume, X and Z-Translation Forces

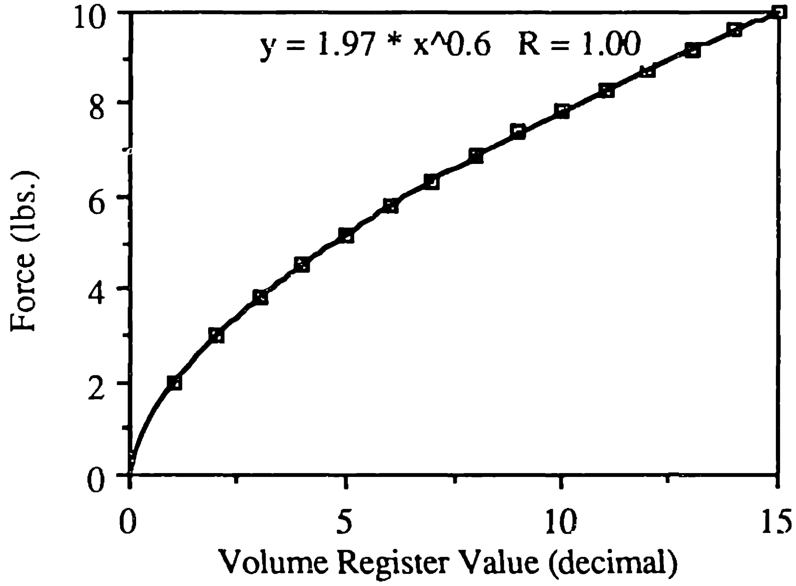

Figure 17 - Force vs. Volume, Y-Translation forces

It was then possible to develop a relationship that would set the loudness level of the tone based on the force reading on an fsr. This relationship is shown in figure 18 for x and z-translation forces, and in figure 19 for y-translation forces.

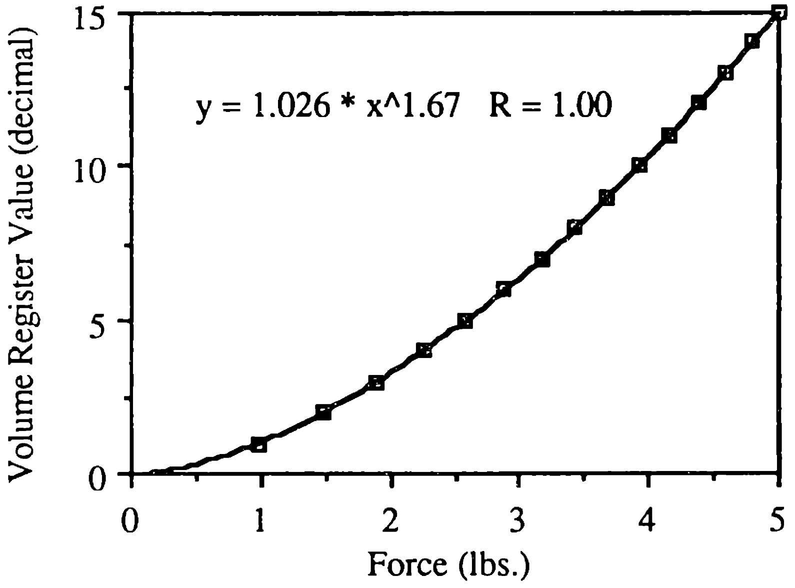

Figure 18 - Volume Level as a Function of Force, X and Z-Translation Forces

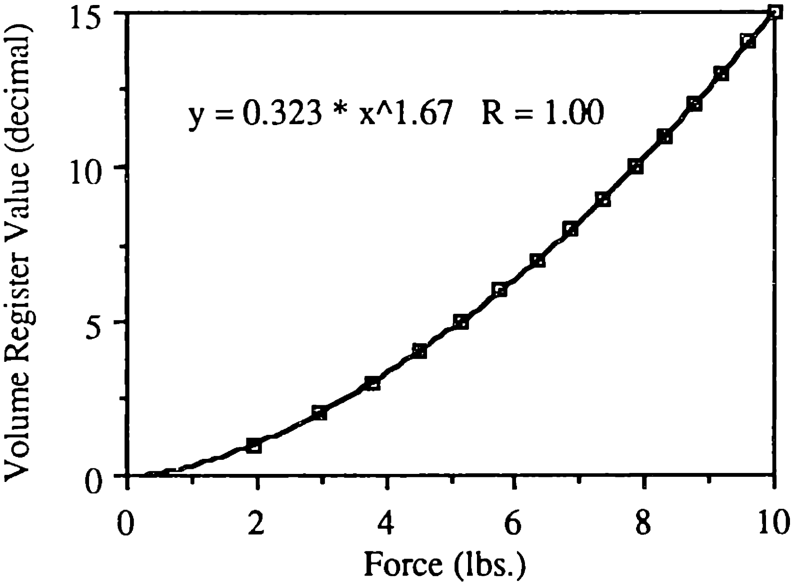

Figure 19 - Volume Level as a Function of Force, Y-Translation Forces

3.3.3 Auditory Display Software

In figures 18 and 19, the volume register values would have been zero (no sound at all) until the force equaled 0.985 pounds in the x or z-directions and 1.97 pounds in the y-direction. The minimum force noticeable by a typical fsr was approximately 0.01 pounds. Therefore, in order to have the display provide stimulation at low levels of force, the equations in figures 18 and 19 were shifted so that a force of 0.01 pounds would register an auditory stimulus at lowest loudness. The relationships used in the software were: volume register value = 1.026*((force + 0.97972)^1.67) for the x and z-directions and volume register value = 0.323*((force + 1.96503)^1.67) for the y-direction. The software flow for the auditory display is shown in figure 20. When first using the display at low force levels, it was noticed that the display made a bad hissing sound and would flutter between being on and off. To overcome this problem, a digital filter was implemented which averaged the past four readings from the fsr to determine the value of the force. Since our sampling rate was 60 Hz this was a reasonable method, and did not slow down the effective sampling rate significantly.

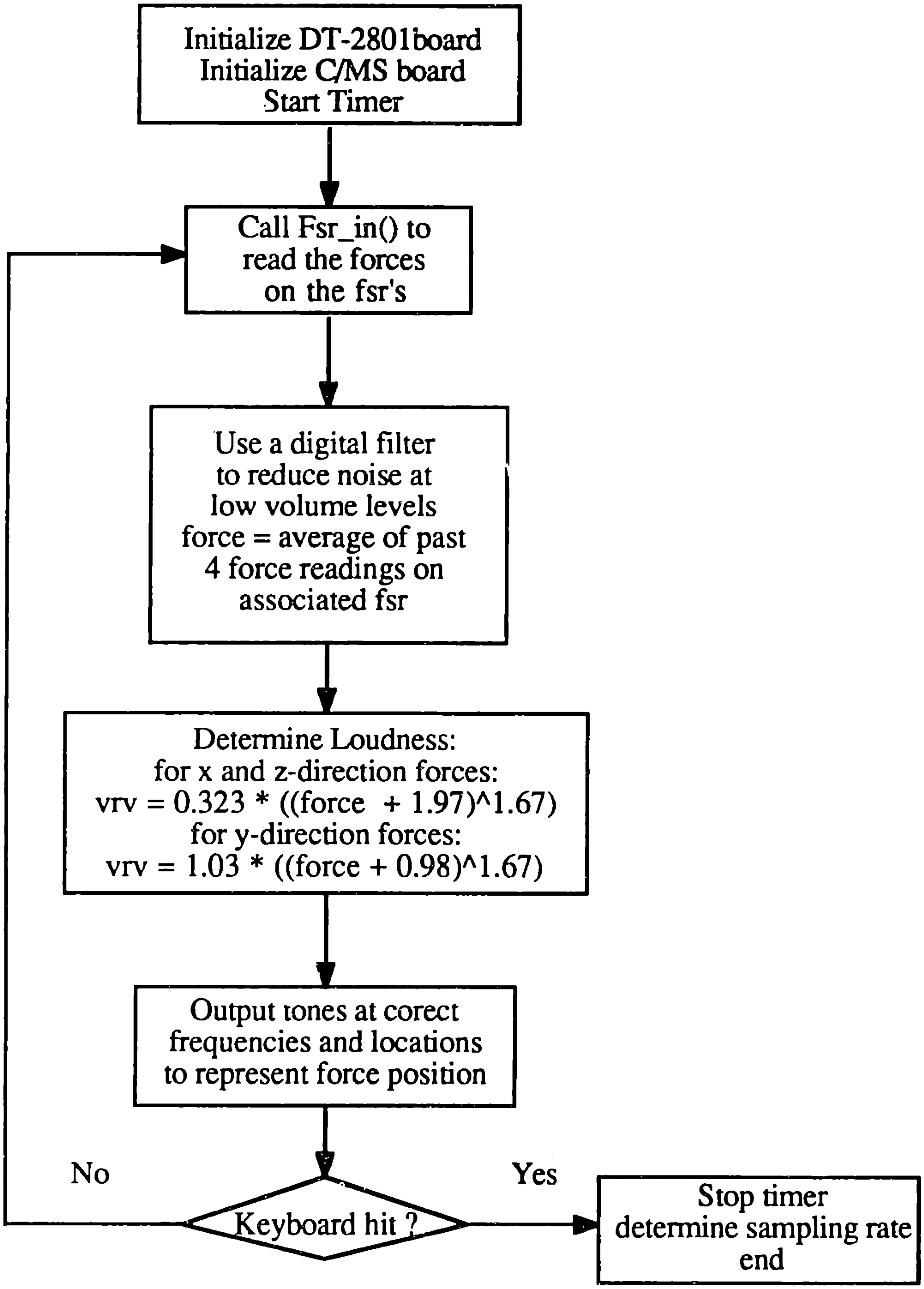

Figure 20 - Auditory Display Software

3.4 Vibrotactile Display

The vibrotactile display, consisted of vibrating voice coils. A detailed overview of the design of the vibrotactile display can be found in [Patrick, 1990]. The vibrators themselves were designed, built, and donated by Audiological Engineering Corporation in Somerville, MA. The displays vibrated at 250 Hz, which is the frequency at which the Pacinian corpuscles (the rapidly adapting vibration detectors in the skin) have their lowest threshold [Barlow & Mollon, 1982]. The resonant frequency of the vibrators used was also 250 Hz, therefore the highest efficiency of voltage into the display and vibration amplitude was achieved. The vibrotactile displays were placed on various locations on the fingertips, palm of the hand, and wrist, depending on the number and location of critical forces present for an experimental task.

These skin locations were selected for two reasons: 1) they are the regions of the skin which are most sensitive to vibrotactile stimulation [Wilska, 1954], and 2) they allowed the displays to be placed in positions which allowed easy transformations through sensory substitution for the subjects to identify the position of the forces exerted at the remote end of the manipulator. Velcro was used to hold the vibrators in place on the skin. The magnitude of vibration was dependent on the magnitude of the force. A drawing of the vibrotactile display is shown in figure 21, and a photograph of a test subject wearing the display on the fingertips while grasping the manipulator hand controller is shown in figure 22.

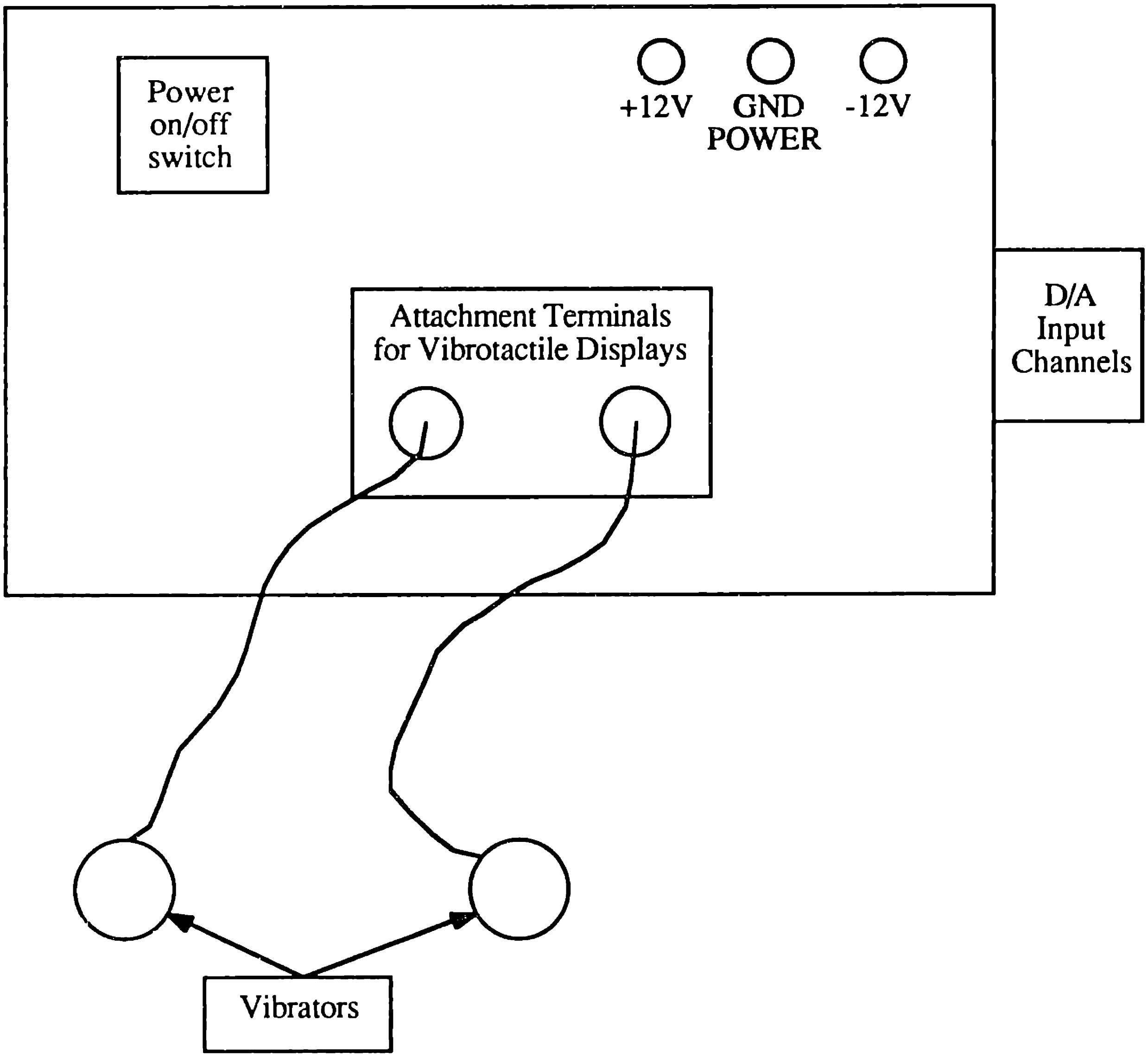

Figure 21 - Vibrotactile Display

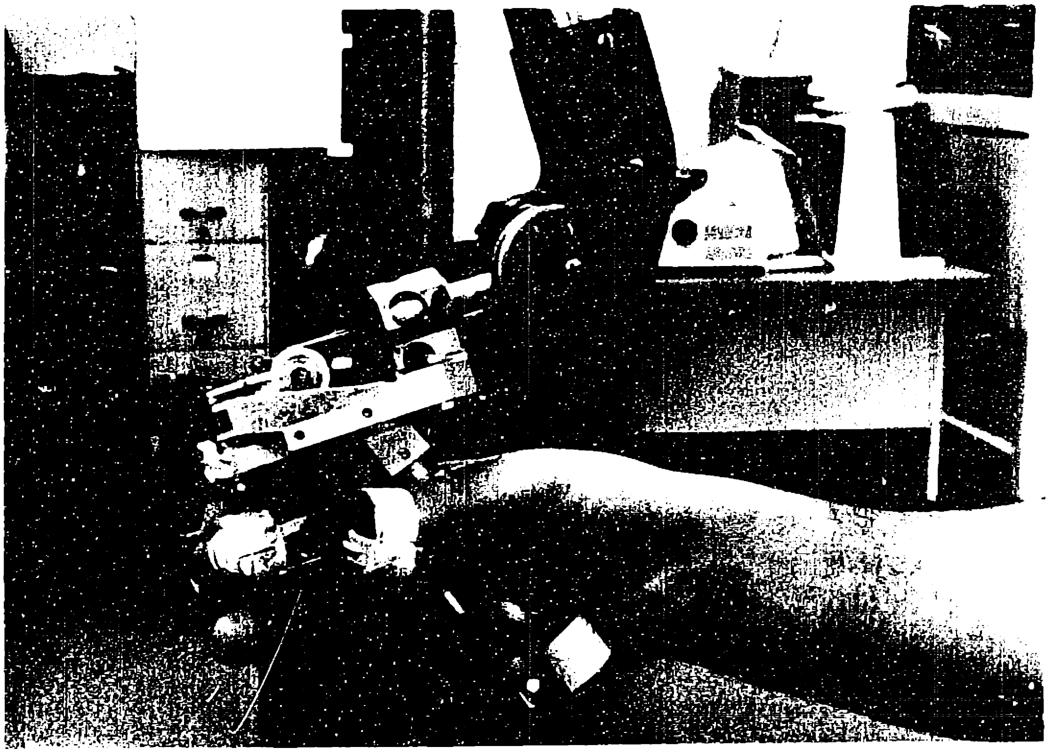

Figure 22 - Two Vibrotactile Displays on Fingertips Being Used with E2 Hand Controller

3.4.1 Calibration of the Vibrotactile Displays

The vibrotactile displays were calibrated by using an accelerometer and the PC. The electronics could accommodate a range of input voltages of zero to two volts. The I/O boards in the PC were used to provide this range of input voltages. An accelerometer was attached to a vibrotactile display to measure the displacement associated with a given input voltage. The displacement was determined by recording the voltage out of the accelerometer circuit, converting voltage out to acceleration, and then converting acceleration to displacement in microns. Figure 23 shows the results of a calibration for a vibrotactile display.

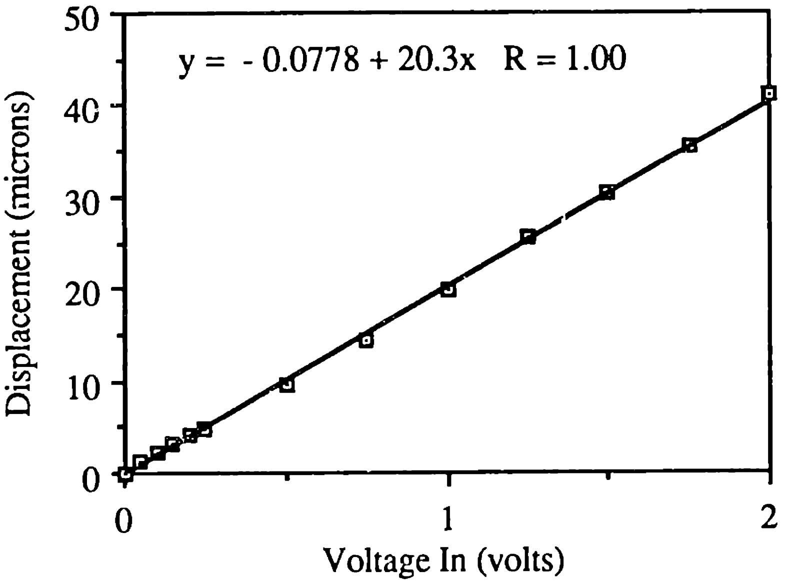

Figure 23 Calibration Results for a Vibrotactile Display

3.4.2 Sensation Magnitude vs. Intensity

Similar to the auditory modality, previous research studies have determined relationships for the perceived magnitude of a vibrotactile stimulus as a function of the physical intensity of the stimulus. The physical intensity is the displacement of the vibrator which is usually measured in microns. Results of the study by Verrillo and Chamberlain [1972] are shown in figure 24.

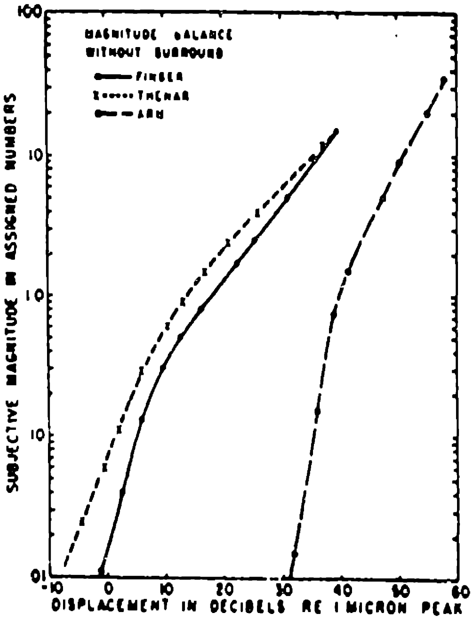

Figure 24 - Sensory Magnitude as a Function of Stimulus Intensity
From [Verrillo and Chamberlain, 1972]

3.4.3 Representing Force as a Change in Sensation Magnitude of a Vibrotactile Stimulus

The function that is shown in figure 24 is: (SM) ^ 0.48 = k * D, where SM is sensation magnitude, and D is displacement in db. Db's are related to displacement in microns by: db = 20 log (P), where P is the displacement in microns. Figure 23 provided a relationship between voltage in and displacement P. Converting displacement in db to displacement in microns, applying the Vin to displacement function, and linearly scaling subjective magnitude between 0 and 5 pounds for x and z-directions and between 0 an 10 pounds for the y-direction, gave the following relationships between force and input voltage: Vin = 0.0493 * (10.0 ^ (0.748 * (force ^ 0.48))) - 0.0493 for forces in x and z-directions and Vin = 0.0493 * (10.0 ^ (0.536 * (force ^ 0.48))) - 0.0493 for forces in the y-direction. The (- 0.0493) was included so that zero force would correspond to zero volts. The relationships are graphed in figures 25 & 26.

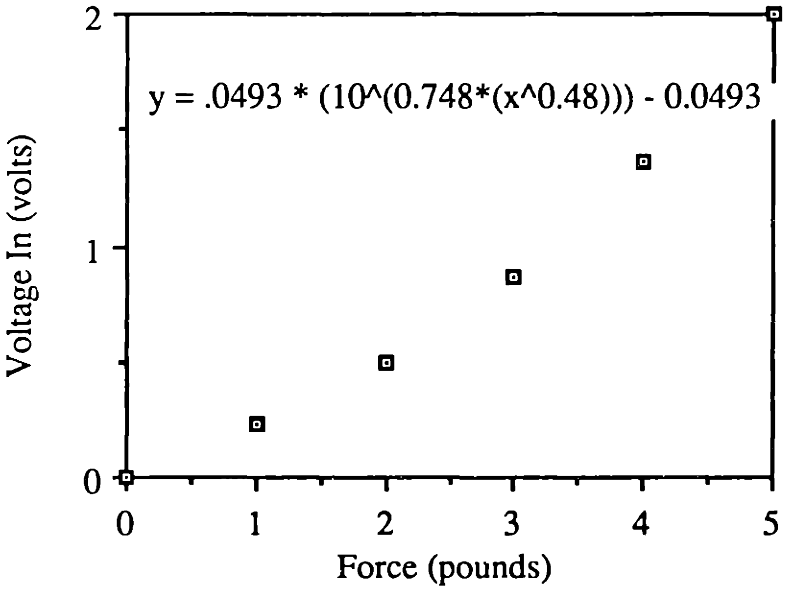

Figure 25 - Input Voltage as a Function of Force, for X and Z-Direction Forces

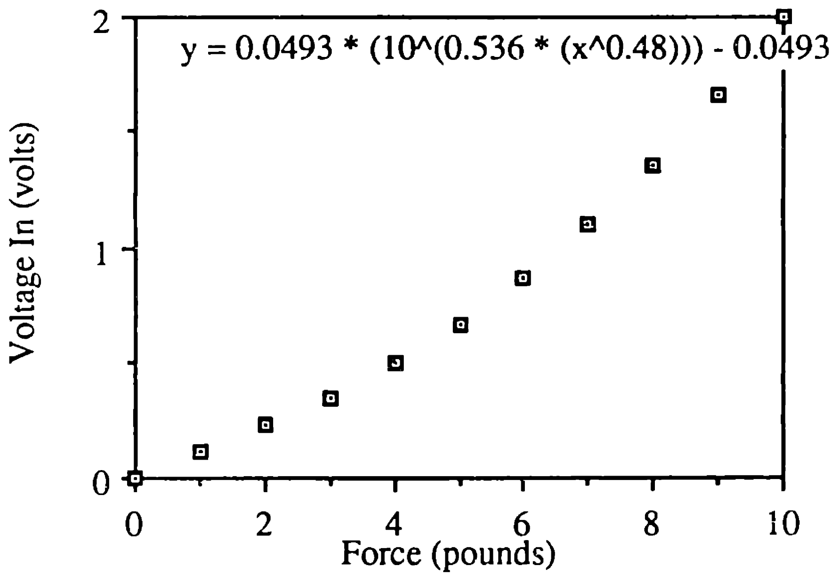

Figure 26 - Input Voltage as a Function of Force, for Y-Direction Forces

These were not however the final equations used in the software. In order to not give either the auditory or vibrotactile displays an unfair advantage over one another during experimentation, the above equations of stimulation were normalized according to equal sensory magnitude scales across the two modalities. S.S. Stevens [1957] showed that the subjective magnitude (X) grows approximately as a power function of the stimulus magnitude (Y) and that each modality has its characteristic exponent. The exponent governs the growth of subjective magnitude as determined by ratio-scaling experiments, mainly by the method of magnitude estimation. If two sensations are governed by the power laws $X1=Y1^m$ and $X2=Y2^n$, it follows that cross-modality matches, in which X1 is equated to X2 will determine an equal-sensation function of the form $Y1=Y2^{n/m}$. In log-log coordinates this equation determines a straight line with a slope equal to n/m [Stevens, 1961].

Stevens [1959] studied these relationships between auditory loudness and vibrotactile intensity. Applying these principles to ensure that the auditory stimulation was comparable to the vibrotactile stimulation , the vibrotactile equations were updated to: Vin =

0.0493 * (10.0 ^ (0.771 * (force ^ 0.48))) + 0.123 for forces in x and z-directions and Vin = 0.0493 * (10.0 ^ (0.553 * (force ^ 0.48))) + 0.126 for forces in the y-direction.

3.4.4 Vibrotactile Display Software

The relationships described above allowed a change in force to be perceived as a change in the magnitude of the vibrotactile stimulus and were used in the software. The software flow for the vibrotactile display is shown in figure 27.

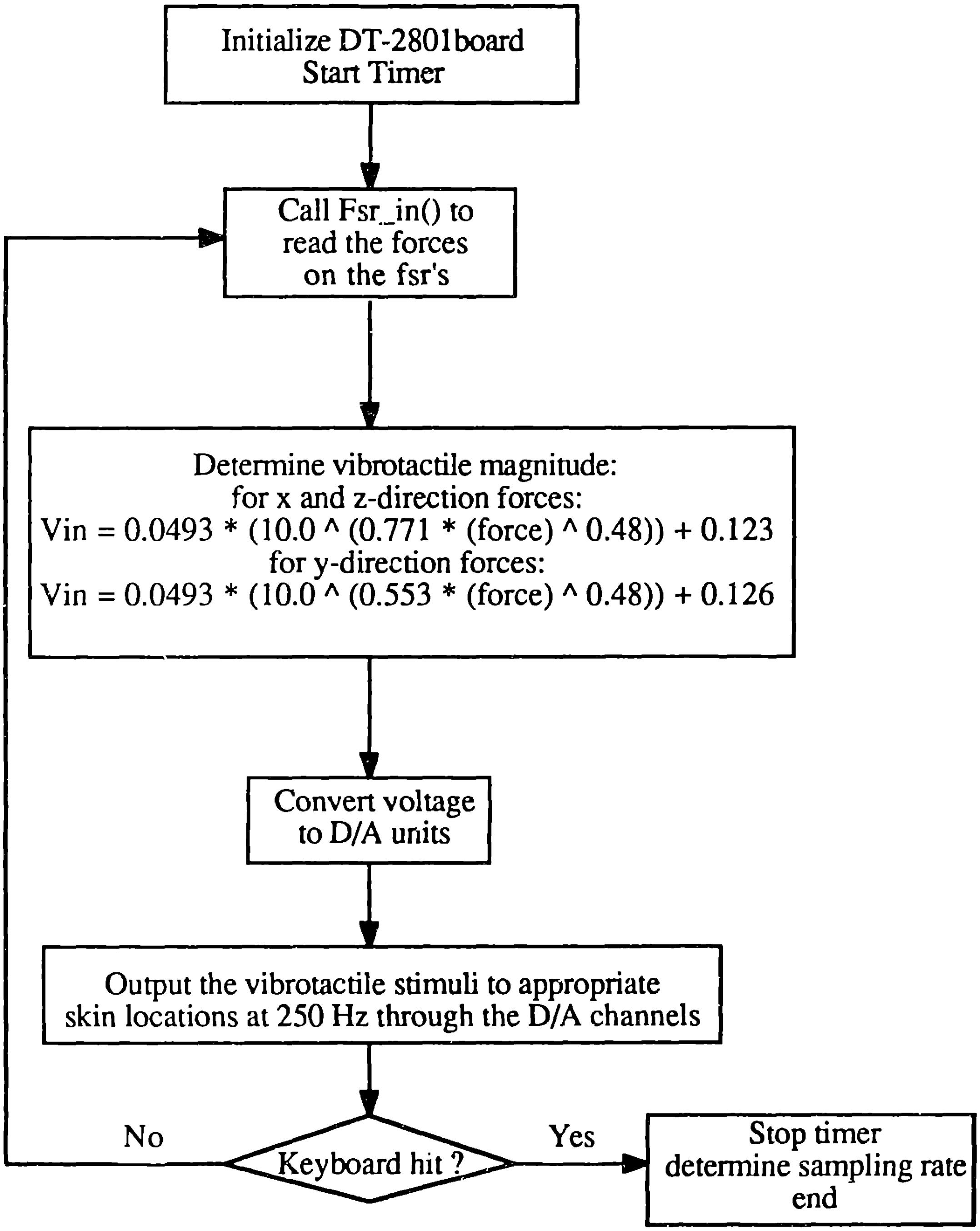

Figure 27 - Vibrotactile Software

3.5 Program Flow

All of the software was written in the C Programming Language. An overview of the program flow is shown in figure 28. After the choice made by the experimenter was entered into the program, the appropriate function was invoked to present force through either the auditory display the vibrotactile display. The boards were initialized and a timer was started to record the system sampling time. All of these tasks were performed by calling separate software functions. A function was called to read the fsr's through the A/D channels. Once the force was known in the software the appropriate level of stimulus was output to the display. During the use of the auditory display, the proper volume level was calculated and output through the C/MS board. If the vibrotactile display option was selected, the proper amplitude of the vibrotactile stimulus was determined by the software and presented through the D/A channels. If a keyboard hit was made, the timer would be stopped, the sampling time calculated and presented on the display screen, and the program would end. If no keyboard hit was made, the fsr function would again be called to determine the forces.

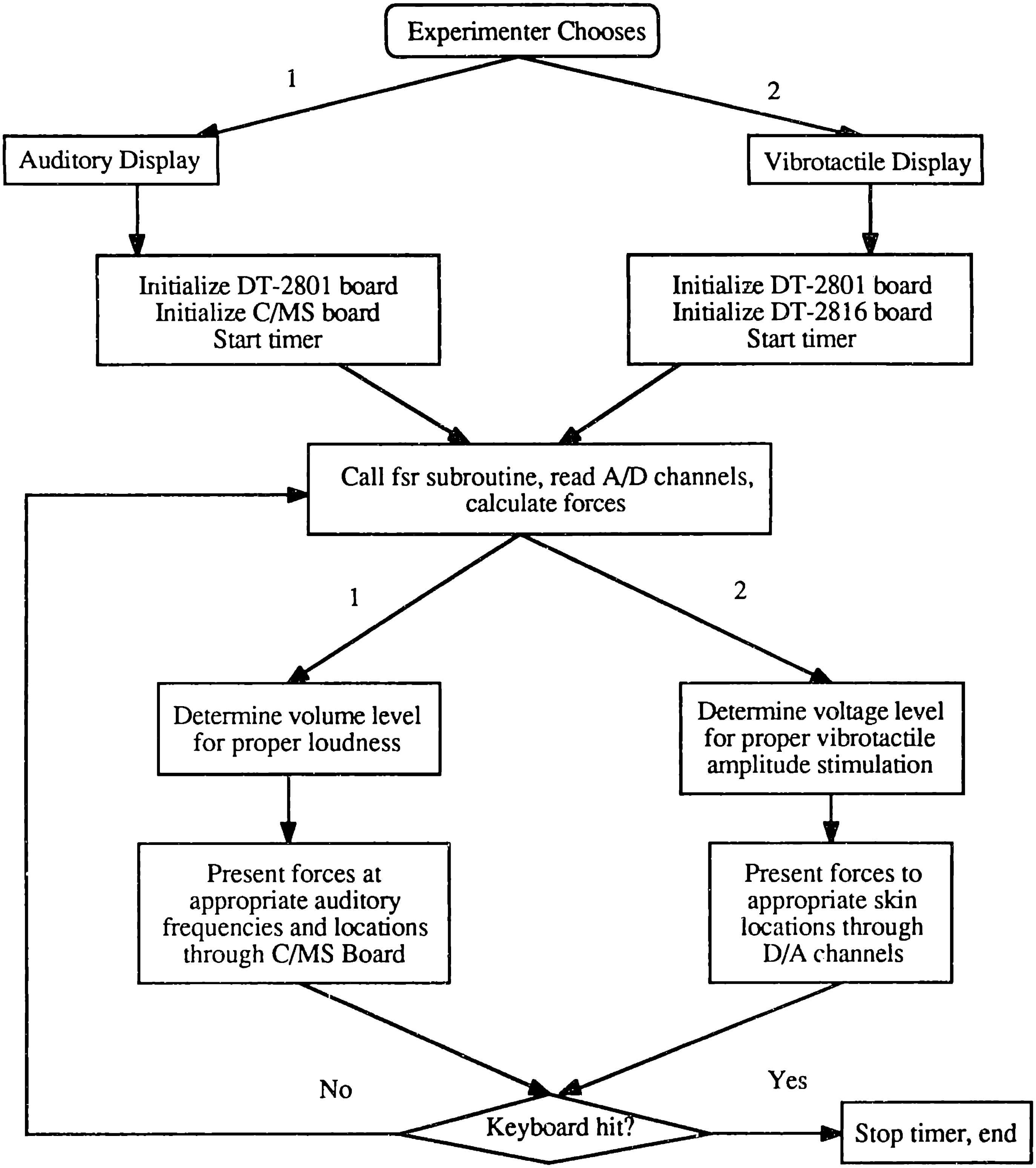

Figure 28 - Program Flow

3.6 E2 Master-Slave Manipulator

The E2 master-slave manipulator located in Man-Machine Systems Laboratory was the manipulator used for experimentation in this thesis. In the late 1940's researchers at the Argonne National Laboratory (ANL) were working on the development of force-reflecting servos [Goertz, 1964]. Their goal was to develop manipulators that could not only have the output at the remote site depend on the input signals from the human operator like the manipulators already being used, but also have the input load at the operator's work station be equal or proportional to the output load at the remote location. The E2 was one of the first electric master-slave manipulators that included force-reflecting servos. Figure 29 displays the E2 in the Man-Machine Systems Laboratory.

The E2 has the capability of operating with direct electronic coupling control both bilaterally with force feedback, and unilaterally without force feedback coming from the slave back to the master arm. Both master and slave arms have seven degrees of freedom including end effector gripping, are geometrically similar, and are isomorphic to the operator's arm and hand. The manipulator degrees of freedom are shown in figure 30, and its dimensions are displayed in figure 31. As can be seen in these diagrams, the E2 possesses six degrees of freedom (dof) plus a gripping capability: three dof (x, y, and z direction) for arm translation, one dof for arm rotation (azimuth), one dof for gripper elevation, one dof for gripper twist, and grasping motion by the gripper jaw. Tracking time delays were considered negligible during the experiments due to the manipulator's quick and accurate response to the operator's input motions [Black, 1970]. A block diagram of the E2 system during master/slave mode is displayed in figure 32.

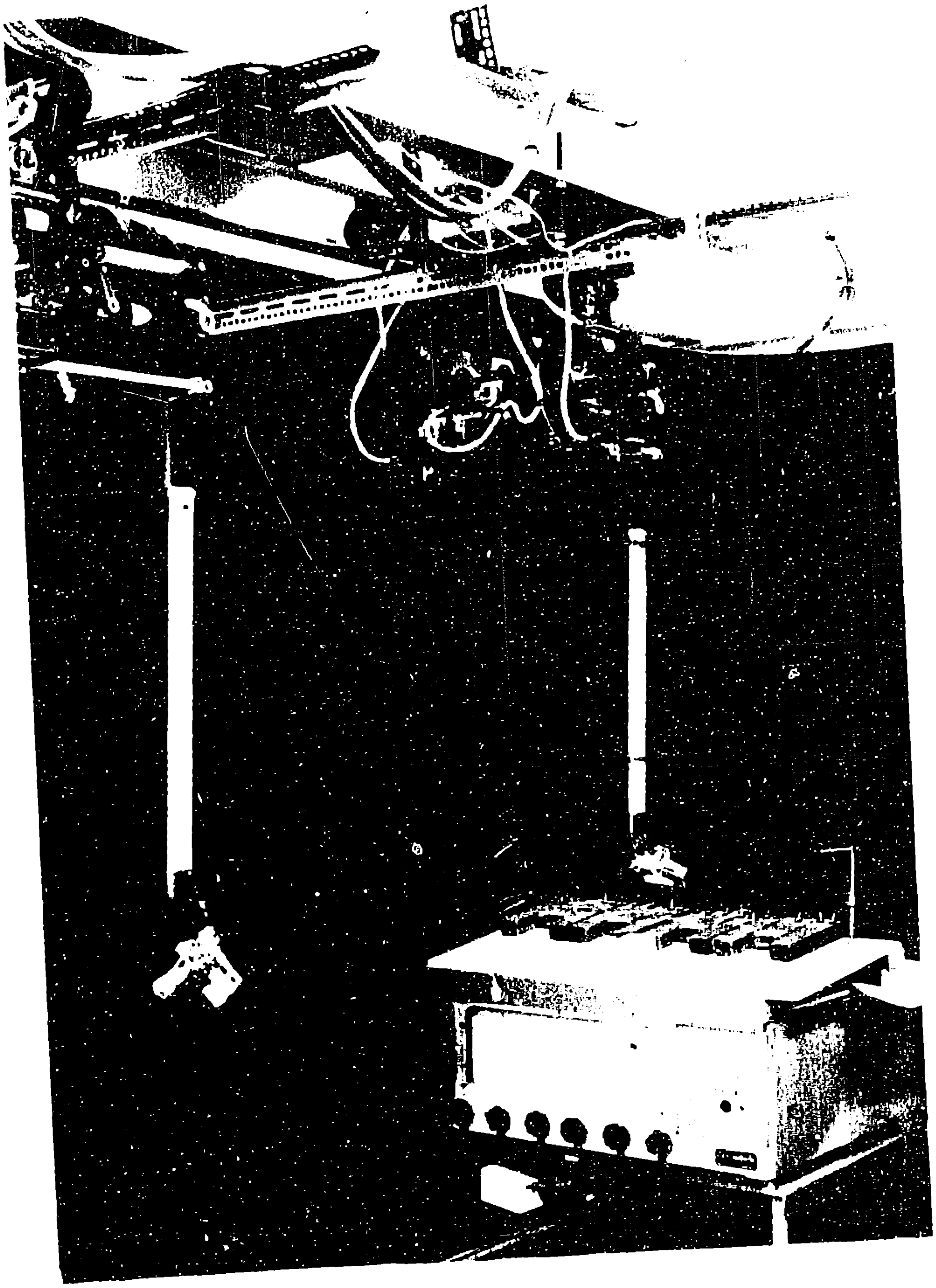

Figure 29 - E2 manipulator in the Man-Machine Systems Laboratory.

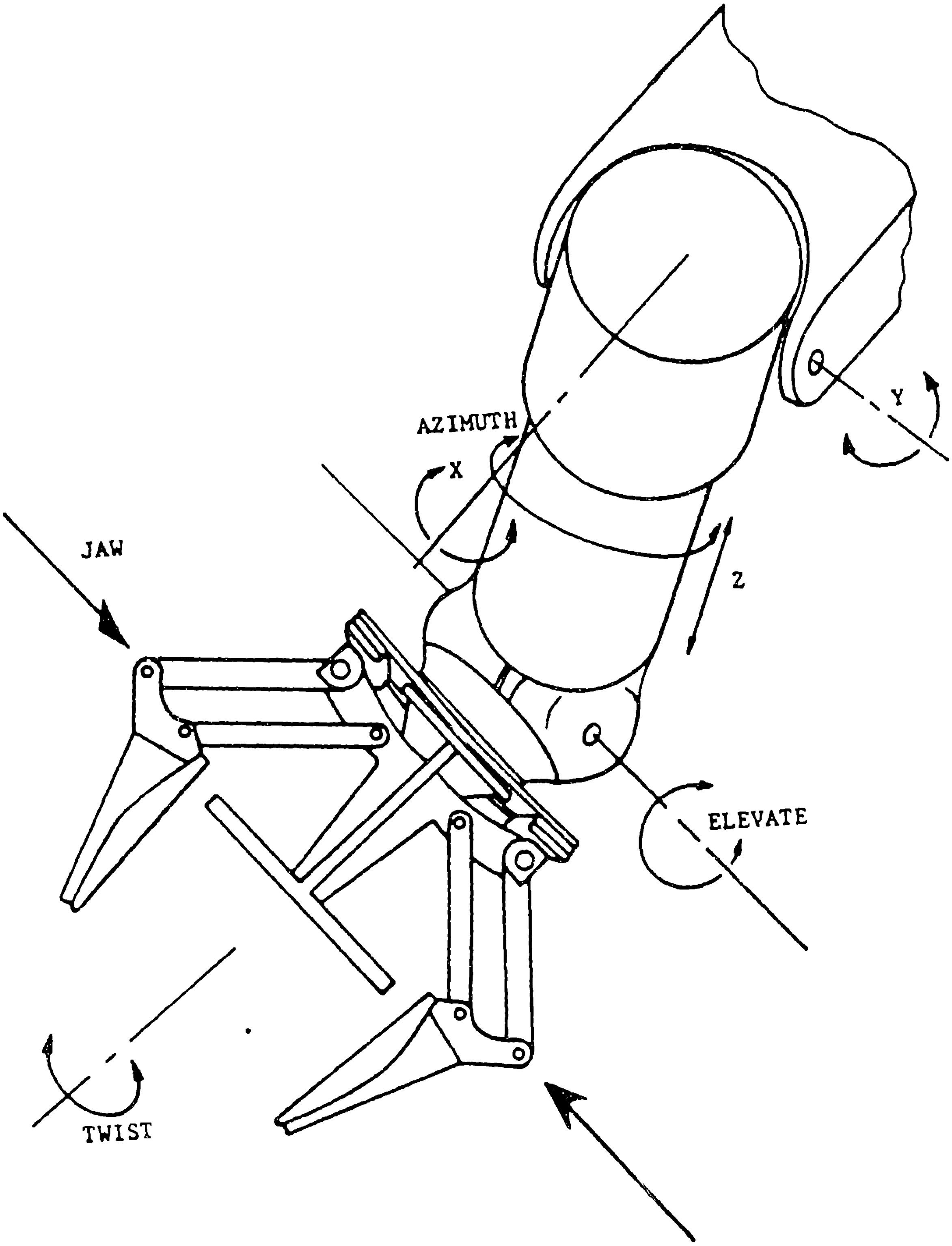

Figure 30 - E2 manipulator degrees of freedom.
Source: [Black, 1970]

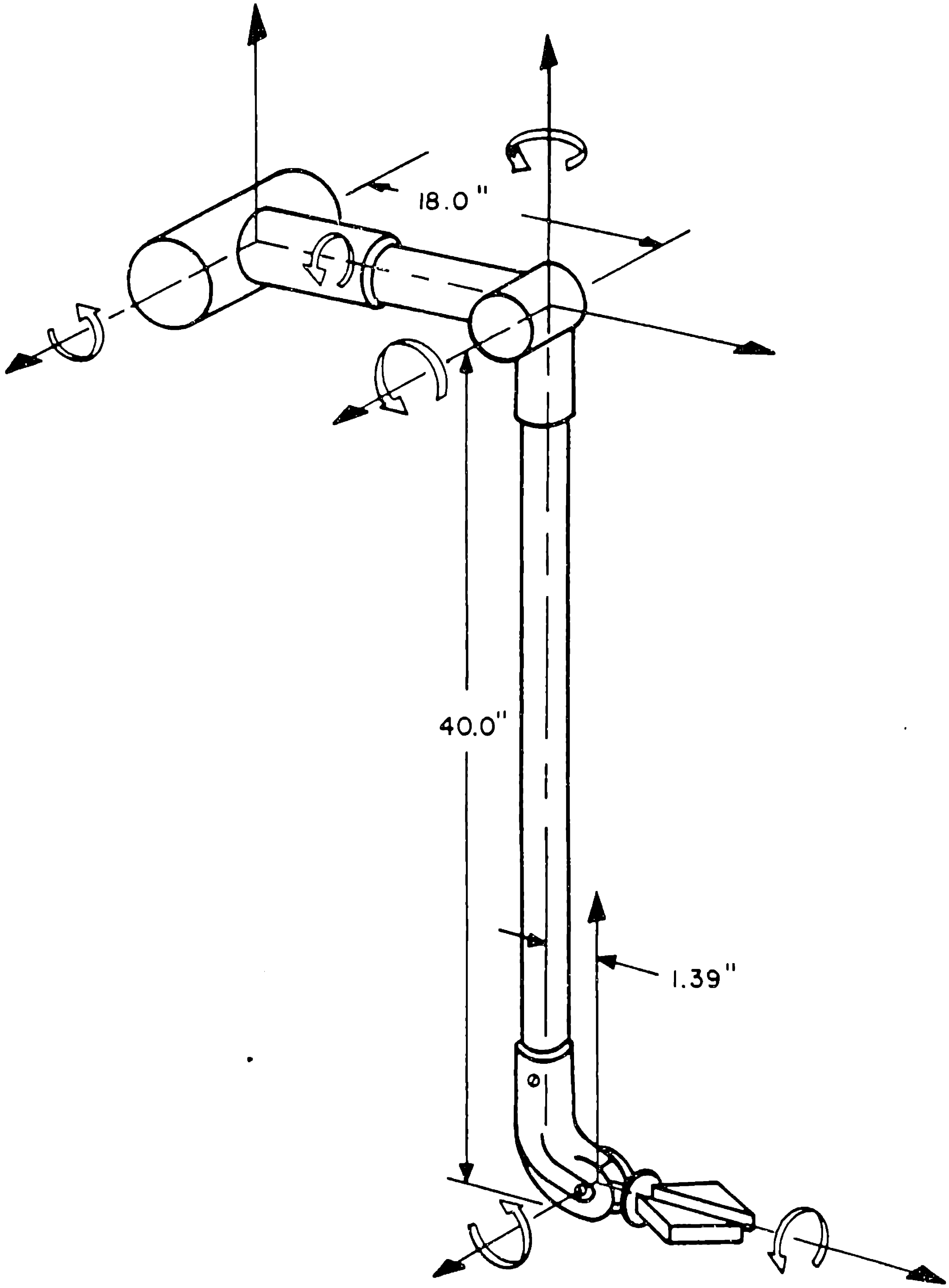

Figure 31 - E2 manipulator dimensions and degrees of freedom.
Source: [Groome, 1972]

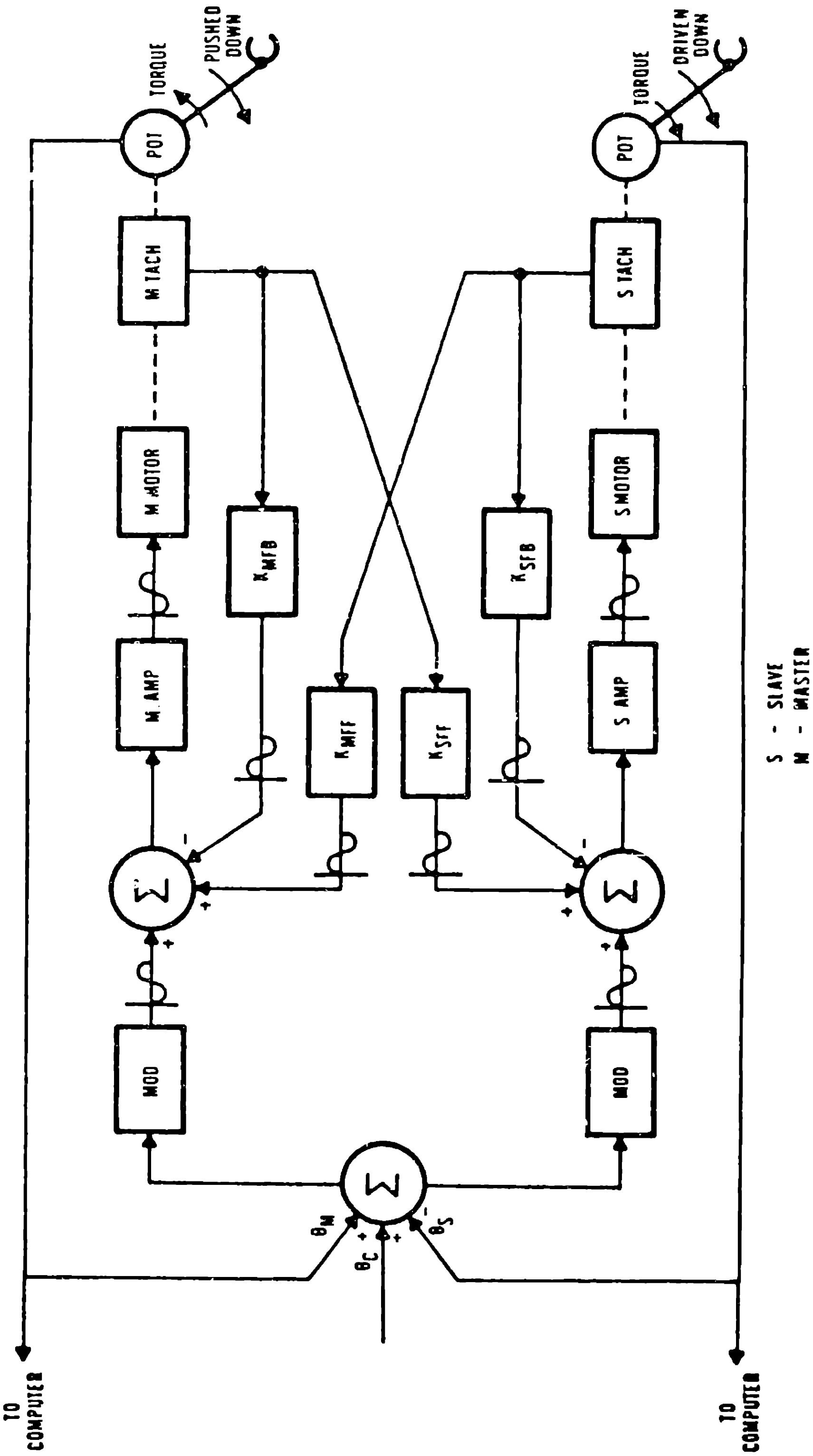

Figure 32 - Block diagram of E2 system during master-slave mode.
Source: [Brooks, 1979]

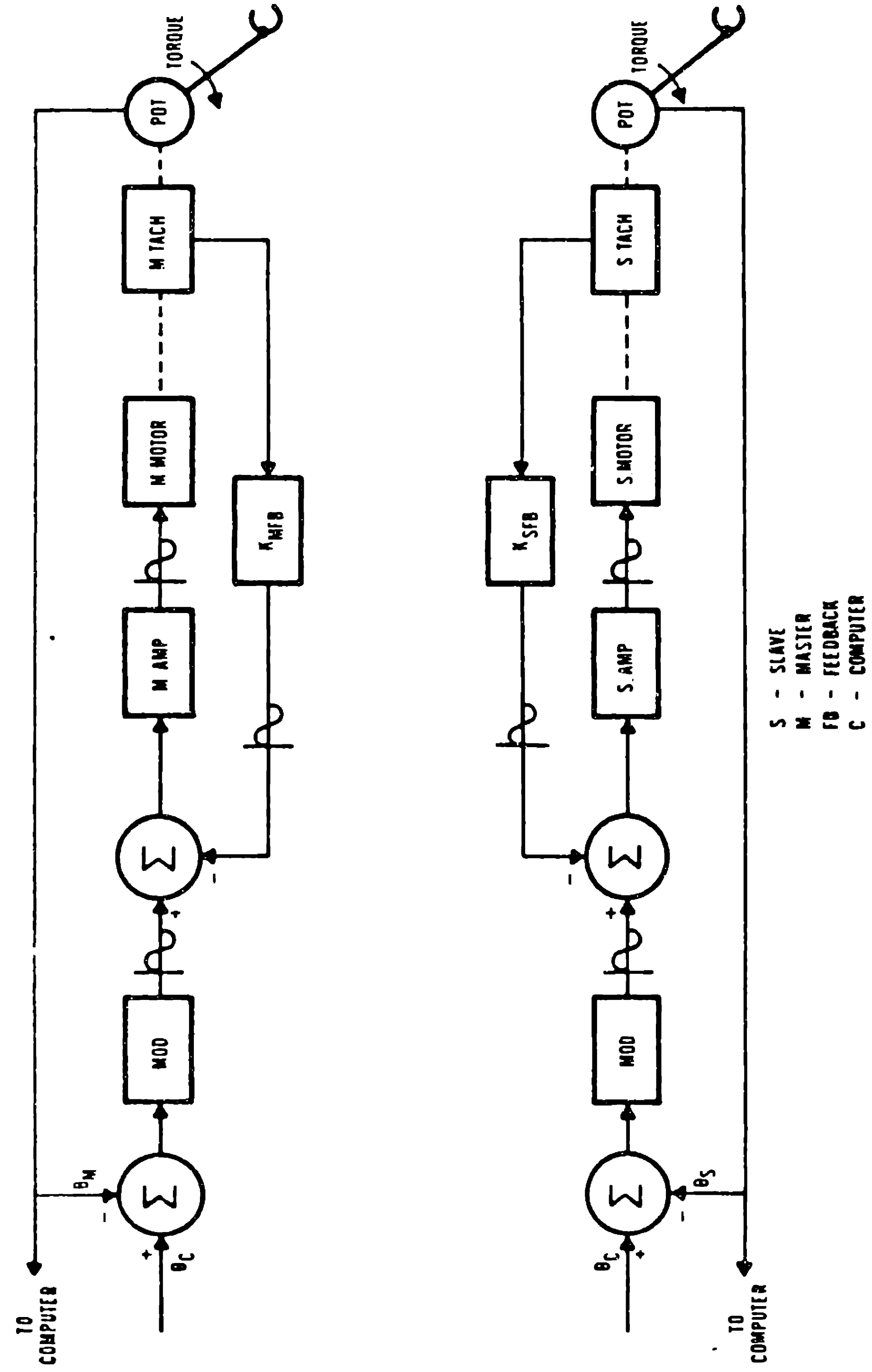

Figure 33 - Block diagram of E2 system during computer control mode.
Source: [Brooks, 1979]

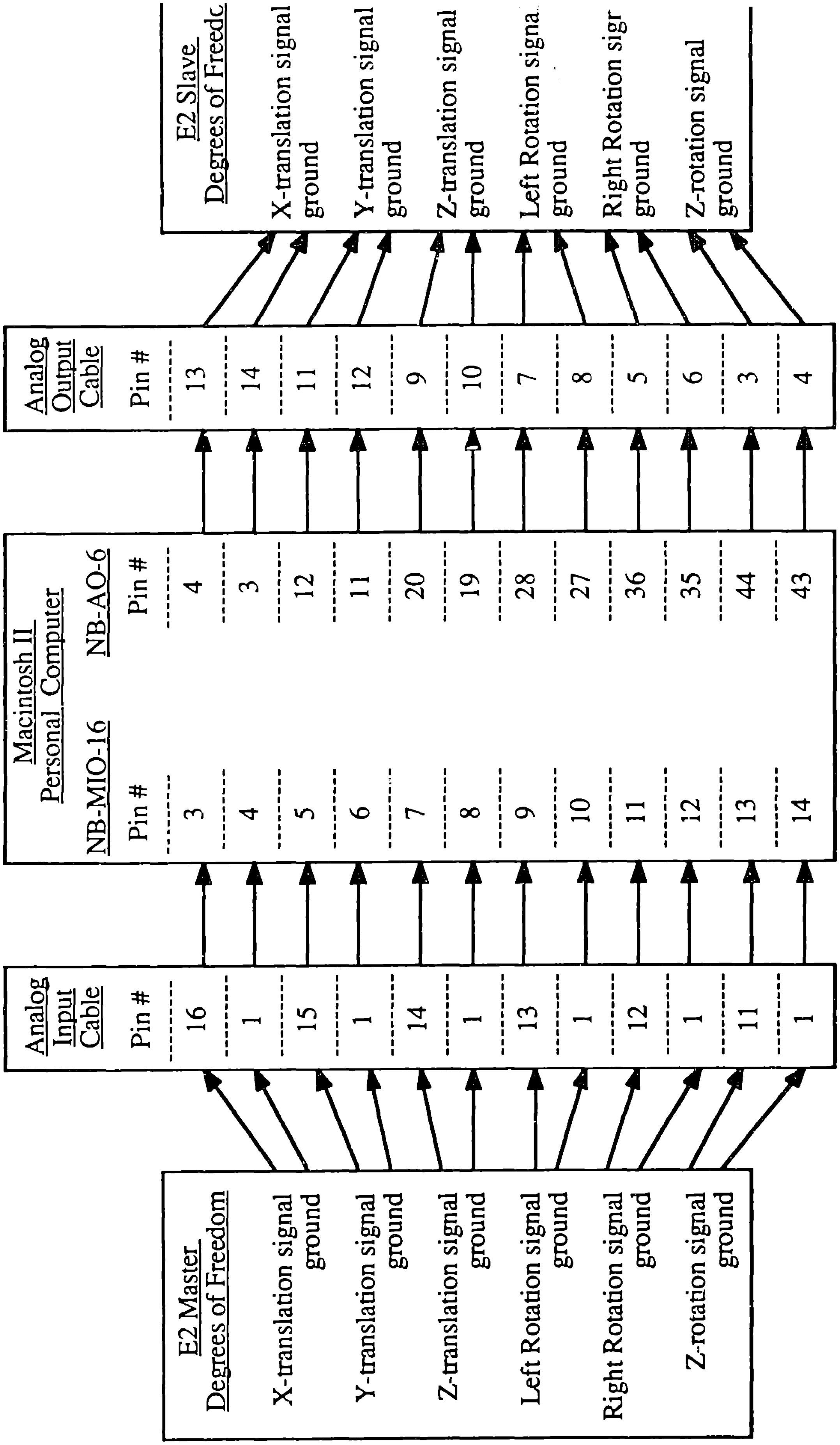

Figure 34 - E2 Time Delay Connections.

3.6.1 Time Delay Capability

The E2 was connected to a Macintosh II Personal Computer to implement a transmission time delay. Figure 33 is a block diagram of the E2 system under computer control, while figure 34 shows a schematic of the E2 connected to the MacIntosh PC. Under time delayed computer control, the six feedforward signals (one for each degree of freedom) from the E2 master are input into the PC through the A/D channels on a National Instruments NB-MIO-16 board. The signal voltage values are then stored for the specified time delay, and then are output to the E2 slave by the PC through the D/A channels on a National Instruments NB-AO-6 board.

Toggle switches on the E2's analog control panel had to be flipped to the "on" position, in order to allow computer control of the E2. In addition, toggle switches were installed to disable the feedforward analog position and tachometer signals from the E2 master to the E2 slave. This enabled only the analog signals from the computer to reach the slave arm. Therefore, these toggle switches allowed the experimenter to create the control mode displayed in figure 33. Performing these procedures enabled computer operation of the E2, and performance of experimental tasks with a transmission time delay.

3.7 Video Monitor

The test subjects were provided with a view of the remote task environment via a television monitor. A Sony monitor displayed a picture 14 inches wide by 10 inches high at a resolution of 512 x 256 pixels. The camera was mounted on a tripod in front of the task board.

4. PSYCHOPHYSICAL EXPERIMENTS

The objective of the psychophysical experiments was to obtain basic information on the characteristics and capabilities of the auditory and vibrotactile displays. Two groups of tests are discussed in this chapter: experiments to determine the number of absolute judgements, and experiments to determine the number of just noticeable differences. A third group of psychophysical experiments was conducted to investigate the display capabilities for representing multiple forces during peg-in-hole tasks, and will be discussed in chapter 6 which focuses on the peg-in-hole experiments. Two additional psychophysical tests were conducted to investigate the capabilities of traditional force feedback, and are presented in chapter 10.

Results from the psychophysical experiments served three major purposes: 1) they provided information that will allow the transfer of the results of this thesis to other systems whose operating characteristics will differ from those in this testbed; 2) they provided information that assisted in making decisions on what modes of presentation were appropriate under a given set of conditions; and 3) they helped determine the characteristics and effectiveness of each of the displays in presenting force information to the operator in order to better anticipate and analyze operator performance for the teleoperator experiments.

4.1 Number of Absolute Judgements

The first psychophysical experiments explored the information channel capacity, or the number of absolute judgements, of the human operator when using the vibrotactile and auditory displays. The amount of input information (Ii) can be expressed in bits and equals the logarithm to the base two of the number of equally likely alternative inputs. The effectiveness of each display was assessed in terms of the relationship between information input into the human operator through the display and the information output response of the human operator. The greater the correlation between input and output, the better the effectiveness of the display [Van Cott & Kinkade, 1972].

4.1.1 Method for Absolute Judgements Experiments

The output (It), or the amount of information transmitted through the human operator channel by each display, was calculated from a two-way data matrix consisting of S stimulus categories and R response categories. The cells of the matrix (S stimulus by R response categories) contained the frequencies with which a particular stimulus produced a particular response. This data allowed the following probabilities to be calculated: 1) P(j,k) = probability of the joining occurrence of a particular stimulus k and a particular response j; 2) P(j) = probability of occurrence of each response j; 3) P(k) = probability of occurrence of each stimulus k; 4) $P_k(j)$ = conditional probability of response j, given stimulus k; 5) $P_j(k)$ = conditional probability of stimulus k having occurred given response j. From these probabilities it was possible to determine It, the amount of information transmitted, from the equation It = Ir - Er. Ir was a measure of response information and equaled $- \sum P(j)\log_2 P(j)$ where j varied from j=1 to j=R. Er was a measure of noise generated within the human operator channel and equaled $- \sum P(k) \sum P_k(j) \log_2 P_k(j)$, where k varied from 1 to S in the first summation and j varied from 1 to R in the second [Van Cott & Kinkade, 1972]. By knowing the amount of input information (Ii) and the amount of transmitted information (It), it was possible to plot Ii versus It. Thus as the amount of input information increases with the number of equally likely alternatives, the amount of transmitted information was determined.

In experiments on absolute judgements, the human operator can be considered to be a communication channel. If the operator's absolute judgements are accurate, then nearly all of the input information will be transmitted successfully. If errors occur, then the amount of transmitted information will be less than the input information. It is reasonable to expect that as the amount of input information is increased, the operator will make more and more errors allowing the limits of the human operator's absolute judgements to be tested. It is also reasonable to expect that as the amount of input information is increased, the amount of transmitted information will increase at first and then will eventually level off at some asymptotic value. This asymptotic value will be the channel capacity of the observer which is the largest amount of information that an operator can ascertain about the stimulus [Miller, 1956].

One bit of information is the amount of information needed to make a decision between two equally likely alternatives. Two bits are needed for four equally likely alternatives, three bits are needed for eight equally likely alternatives, and so on. Therefore if experimentation determined that the channel capacity for a certain display was 2.5 bits, then the number of absolute judgements that could be expected by an operator using that display would be 2^(2.5) = 5.66 or approximately 6 absolute levels.

Four test subjects participated in the psychophysical experiments on absolute judgements, and each began by trying to distinguish between three different frequencies. As the session continued, the number of stimuli in a grouping were increased to four, five, six, seven, and ten different stimuli. Each subject received each stimulus within a group four times for a total of 16 x n trials per group, where n was the number of stimuli within a group. The subjects were trained and given practice in recognizing different frequencies and assigning numbers to each stimulus in a group. Each stimulus was presented for 2.5 seconds. The subject then responded by assigning a number to that stimulus. After responding, the subject was told whether or not the response was correct, and if it was incorrect the subject was told the correct response. This process continued until all trials for that group was completed. Before each group of tones was presented, the subject was given some warm-up and practice trials in order to more easily adjust to the increased number of stimuli in the new group.

4.1.2 Absolute Judgements with the Auditory Display

Channel capacity experiments were conducted using auditory stimuli varying in loudness to test the auditory display. Garner [1953] used combinations of 4, 5, 6, 7, 10, and 20 different sound intensities over a range of 15 to 110 db. He found the channel capacity for absolute judgements of loudness to be 2.3 bits, or approximately five discriminable alternatives.

For the experiments conducted with the auditory display in this thesis, the stimuli were spaced by equal sensation magnitude based on the sone scale (see figure 13) between 46 to 70 db SPL. A 1000 Hz auditory tone was presented to both ears simultaneously. A channel capacity of approximately 1.76 bits representing approximately 3.4 absolute judgements was determined. The detailed results of these tests are displayed in table 1 and figure 35.

Number of Stimuli	Ii (bits)	Ir (bits)	Er (bits)	It (bits)	No. of Abs. Judgements
3	1.585	1.583	0.1124	1.471	2.772
4	2.0	1.982	0.3427	1.639	3.115
5	2.322	2.315	0.5514	1.763	3.395
6	2.585	2.567	0.9386	1.628	3.091
7	2.807	2.775	1.102	1.673	3.19
10	3.322	3.294	1.618	1.676	3.195

Table 1 - Results for Absolute Judgements Experiments with the Auditory Display

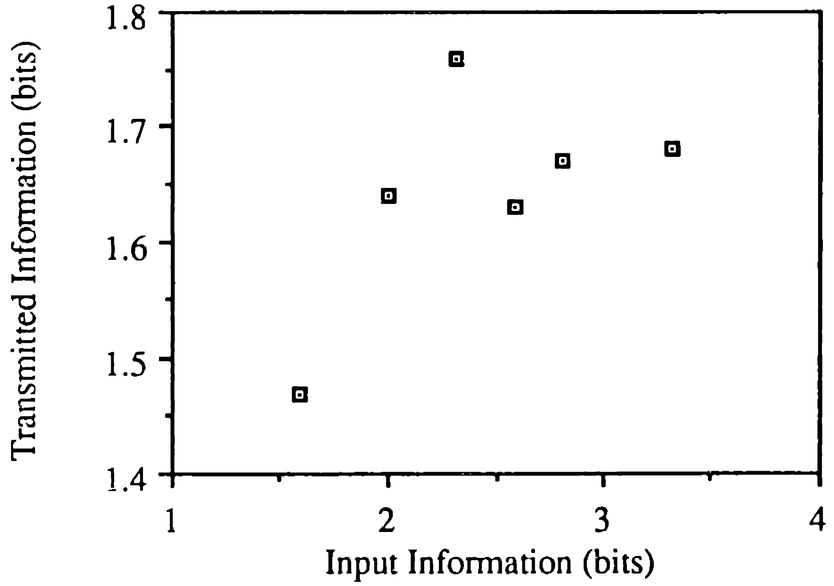

Figure 35 - Channel Capacity Results for the Auditory Display

4.1.3 Absolute Judgements with the Vibrotactile Display

Geldard [in Miller, 1956] measured the channel capacity for intensity of vibrotactile stimuli in the chest region. He found the channel capacity to be approximately 2 bits or 4 possible absolute judgements.

The vibrotactile display used in the testbed described in Chapter 3 allowed amplitude modulation of a 250 Hz vibratory signal with an amplitude range of 7 to 32 db (re 1 micron). This range was divided into sections of equal sensation magnitude (see figure 24) for the absolute judgements experiments. The 250 Hz vibratory signal was presented simultaneously to the index finger and thumb. A channel capacity of approximately 1.76 bits representing approximately 3.4 absolute judgements was determined. The detailed results of these tests are displayed in table 2 and figure 36.

Number of Stimuli	Ii (bits)	Ir (bits)	Er (bits)	It (bits)	No. of Abs. Judgements
3	1.585	1.583	0.0	1.585	3.0
4	2.0	1.996	0.353	1.643	3.123
5	2.322	2.314	0.5871	1.727	3.31
6	2.585	2.578	1.031	1.547	2.923
7	2.807	2.803	1.094	1.709	3.268
10	3.322	3.286	1.527	1.76	3.39

Table 2 - Results for Absolute Judgements Experiments with the Vibrotactile Display

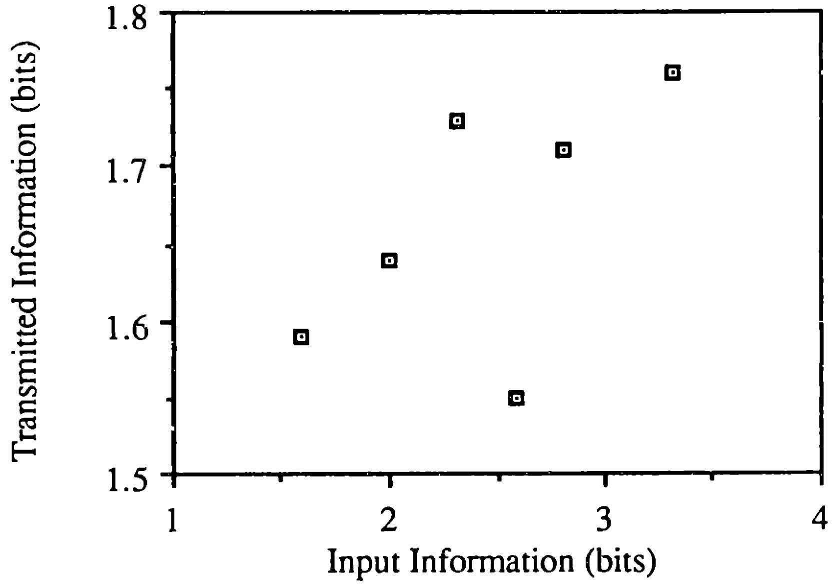

Figure 36 - Channel Capacity Results for the Vibrotactile Display

4.1.4 Absolute Judgements with Auditory Frequency

In addition to testing the auditory and vibrotactile displays, absolute judgement experiments on auditory frequency were also included. As was stated in Chapter 3, auditory frequency (along with auditory localization) was used to help the test subjects identify the position of a force during tasks that involved multiple force positions. Therefore an understanding of the subjects' ability to absolutely identify a number of distinct frequencies helped in determining how many force positions could be identified by the subject. Thus absolute judgements experiments on auditory frequency were conducted.

Test subjects were presented with a number of tones varying in frequency and were asked to assign a number to each tone. The number of tones (different pitches) were increased until the channel capacity was determined. Pollack [1952] asked test subjects to identify tones that differed in frequency by assigning numbers to each tone. He used a range of 100 to 8000 Hz in equal logarithmic steps. No mistakes were made by the subjects when only two or three alternatives were presented. Mistakes were infrequent with four alternatives and became increasingly more frequent as the number of alternatives increased beyond four. The number of alternatives were increased from 2 to 14 which represented a range of input information of 1 to 3.8 bits. Pollack found that the amount of transmitted information reached a peak at approximately 2.5 bits which was thus the channel capacity for absolute judgements of pitch. This capacity corresponded to 6 equally likely alternatives.

During the absolute judgements experiments on auditory frequency for this thesis, the stimuli were spaced equally on a logarithmic scale from 28 to 3500 Hz. The tones were simultaneously presented to both ears at an intensity of approximately 65 db spl. The results were similar to the those obtained by Pollack, channel capacity was approximately 2.18 bits or 4.5 absolute judgements. The detailed results of these tests are displayed in table 3 and figure 37. A summary of results for the auditory display, vibrotactile display, and auditory frequency for the absolute judgements experiments is shown in table 4.

Number of Stimuli	Ii (bits)	Ir (bits)	Er (bits)	It (bits)	No. of Abs. Judgements
3	1.585	1.583	0.0	1.585	3.0
4	2.0	1.999	0.08432	1.915	3.77
5	2.322	2.319	0.1349	2.184	4.54
6	2.585	2.573	0.5247	2.048	4.14
7	2.807	2.796	0.7459	2.05	4.14
10	3.322	3.311	1.333	1.978	3.94

Table 3 - Results for Absolute Judgements Experiments with Auditory Frequency

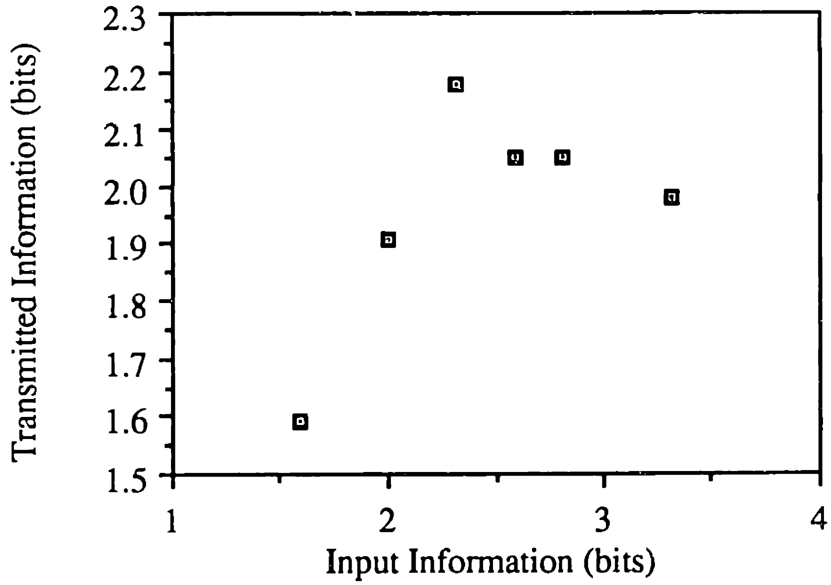

Figure 37 - Channel Capacity Results for the Vibrotactile Display

Stimulus Type	Channel Capacity	Number of Absolute Judgements
Auditory Display	1.76 bits	3.4
Vibrotactile Display	1.76 bits	3.4
Auditory Frequency	2.18 bits	4.5

Table 4 - Summary of Results for Experiments on Absolute Judgements

4.2 Relative Discrimination (JND) Experiments

In many teleoperation tasks an operator needs to distinguish whether an applied force is increasing or decreasing over time. In order to calibrate the effectiveness of the vibrotactile and auditory displays to present this information, tests on relative discrimination to determine just noticeable differences (JNDs) were conducted. These tests determined the operator's ability to detect a small difference between two stimuli or a change in one stimulus. The least change in a stimulus or the least difference between two stimuli that can be detected is called the Just Noticeable Difference (JND) which is also expressed as ΔI to represent a change in intensity [Van Cott & Kinkade, 1972].

Weber proposed that the ratio between the stimulus intensity and ΔI is constant [Stevens, 1951], $\Delta I/I = K$ over a range of stimuli where K is a constant known as the Weber fraction and I represents the reference stimulus magnitude. Thus as the reference stimulus increases, the change in the stimulus magnitude necessary for the operator to detect a change in the stimulus also increases.

4.2.1 Relative Discrimination with the Auditory Display

The C/MS card had four bits for volume control, providing fifteen discrete loudness levels between 46 and 70 db SPL. Therefore a maximum of 14 JND's were possible. These levels were tested and all fifteen levels were easily identifiable when presented relatively from one to the next, thus providing 14 JND's for the auditory loudness display. The relationships between ΔI and I, and ΔI/I and I for the auditory display are shown in figures 38 and 39. These figures do not exhibit a tendency towards Weber's theory since the discrete loudness changes were probably greater than the JND's that would be observed if continuous scale changes were possible. This was a limitation of the C/MS card and, in effect, made it impossible to get ΔI small enough to determine the number of JND's that would be present over the tested range if the capability to test smaller changes existed. Therefore figures 38 and 39 do not agree with previous research research [Stevens, 1951], [Rabinowitz, Lim, Braida, and Durlach, 1976] where smaller changes in ΔI than those used with this testbed were possible.

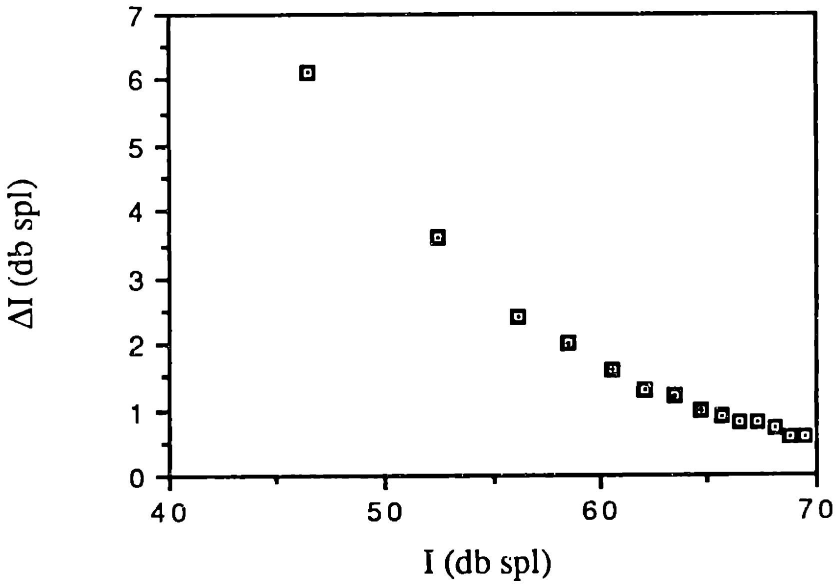

Figure 38 - ΔI versus I for the Auditory Display

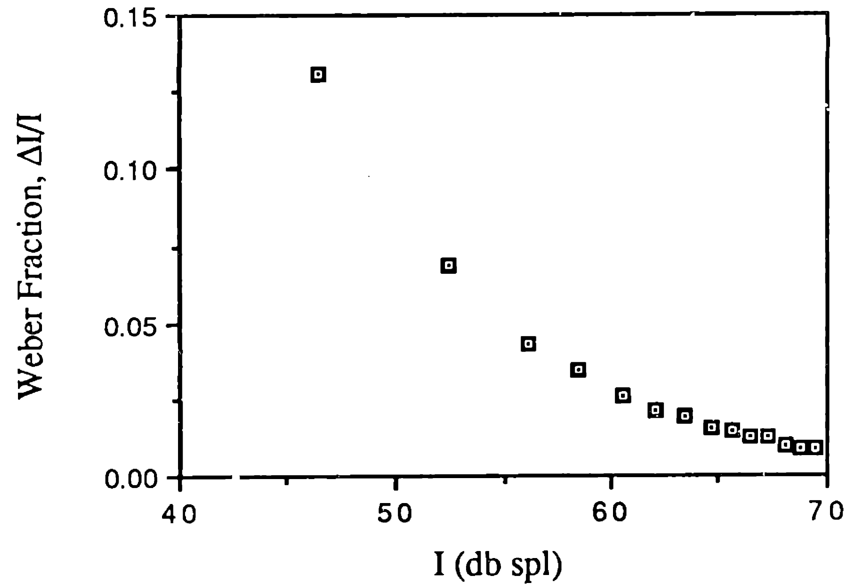

Figure 39 - ΔI/I versus I for the Auditory Display

4.2.2 Relative Discrimination with the Vibrotactile Display

The vibrotactile display, unlike the auditory display, presented changes in magnitude continuously. In order to determine the number of JND's an up and down method was used [Campbell, 1963], [Levitt, 1970]. The intensity scale was split into five sections of equal subjective sensory magnitude, and the mid-point of each section was used as a base intensity (I). The five base intensities were 4.15, 8.68, 14.8, 22.9, and 33.4 microns. The base intensity was presented along with another stimulus of higher intensity (I + Δ I). Each stimulus was presented for 1 second with a pause in between of 2 seconds. The procedure was a series of symmetrical two interval two alternative forced choice tests, and the subject was required to respond whether the first or second stimulus was of greater magnitude. Three tests subjects were used, and the results for each subject were averaged to determine the number of JND's. Each subject received the base intensity groupings in different random orders. The ordering of presenting I and I+ΔI was determined by using a random number generator on the PC.

If the subject recorded two correct responses in a row, ΔI was lowered. If the subject recorded one incorrect response, ΔI was raised. Each time the direction of the changes in ΔI was reversed, a transition point was recorded. The testing continued as the changes in ΔI moved up and down until eight transition points occurred. A sample of the results of this method for a subject at a base intensity of 8.68 microns is shown in figure 40.

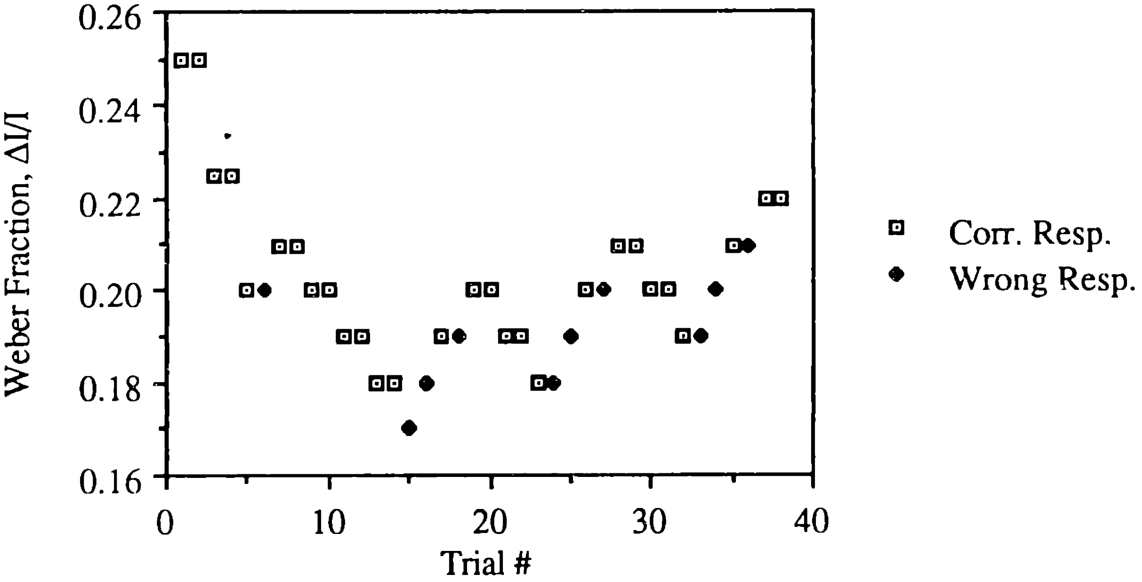

Figure 40 - Sample Results for Method Used During Vibrotactile Display JND Experiments

The Weber ratio [Stevens, 1951], ΔI/ι, was recorded at each transition point and averaged for that intensity level. The ratios for each of the five base intensities were averaged for the test subjects and the number of JND's were determined over the full range of the vibrotactile display. Table 5 shows the results. Figure 41 displays the relationship between ΔI and I and figure 42 shows the relationship between ΔI/I and I.

Base Intensity, I (microns)	ΔI (microns)	Weber fraction, ΔI/I
4.15	0.996	0.24
8.68	1.91	0.22
14.8	3.11	0.21
22.9	4.12	0.18
33.4	6.01	0.18

Table 5 - Results from Vibrotactile Display JND Experiments

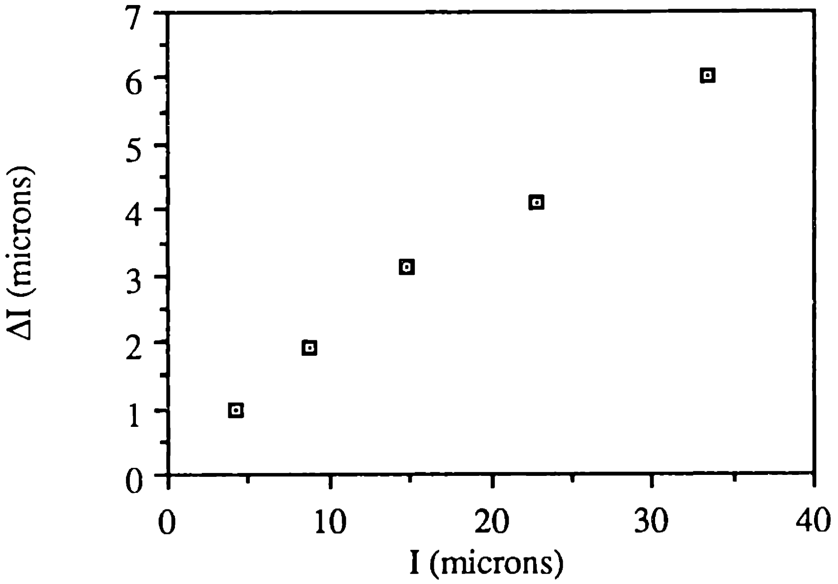

Figure 41 - ΔI versus I for the Vibrotactile Display

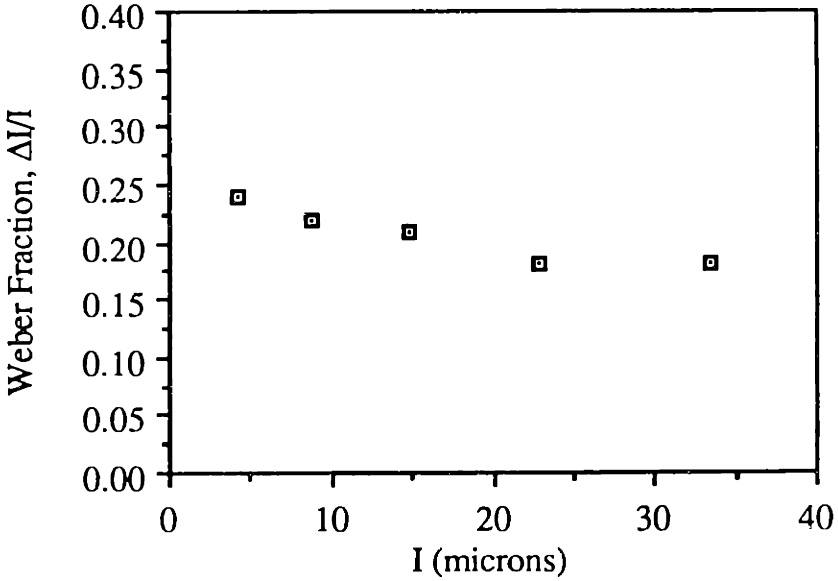

Figure 42 - ΔI/I versus I for the Vibrotactile Display

The average ΔI/I (Weber's fraction) over the entire range was approximately 0.21, and approximately 15 JND's were observed for the vibrotactile display between 7 and 32 db (re: 1 micron). In a previous study Craig [1972] used a similar experimental method with a 160 Hz vibrotactile stimulus on the fingertip. Craig found that the Weber fraction was 0.2 and exhibited virtually no change over a range of displacement amplitudes of 30 db.

To a good approximation "Weber's Law" usually holds in most cases, however there have been updates to "Weber's law" as a result of further studies [Stevens, 1951]. One such study was conducted by Rabinowitz, Lim, Braida, and Durlach [1976] who found the ratio to decrease as the intensity increased for auditory loudness. As can be seen in figure 42 and table 5 in the vibrotactile case, ΔI/I tended to decrease as vibrotactile intensity increased. This trend agrees with the results found by these other researchers.

5. MEASURING THE REPRESENTATION OF BASIC FORCE INFORMATION THROUGH OBJECT CONTACT EXPERIMENTS

Teleoperator experiments were conducted with the E2 master-slave manipulator to test the effectiveness of the auditory and vibrotactile displays in aiding teleoperator performance by representing force feedback through sensory substitution. These experiments were conducted in the Man-Machine Systems Laboratory and utilized the E2 master-slave manipulator, sensors, and displays described in Chapter 3.

The experiments discussed in this chapter concentrated on object contact tasks and measured: 1) the usefulness of sensory substitution in presenting the presence of a contact force, 2) the usefulness of sensory substitution in presenting information on the magnitude of a contact force, and 3) the usefulness of sensory substitution in presenting information for tracking the changes in magnitude of a sustained contact force. The subjects were required to alternately contact two objects with the tip of the E2 manipulator. The three task scenarios relating to each of the above mentioned three tasks were: 1) moving instantaneously between fixed objects, 2) moving instantaneously between movable objects, and 3) moving between movable objects but maintaining contact with each object for three seconds before moving on to the next object.

5.1 Presence of Contact Forces

The objective of these experiments was to test the representation of the presence of a contact force through sensory substitution. Detection of the presence of a force was critical, not the magnitude of the force. Applications for this task include rendezvous and docking when the operator needs to know when he/she comes into contact with the target vehicle, and telemanipulation when the operator needs to perform an operation on a piece of equipment and has to know when contact has been made to prevent further motion and possible damage.

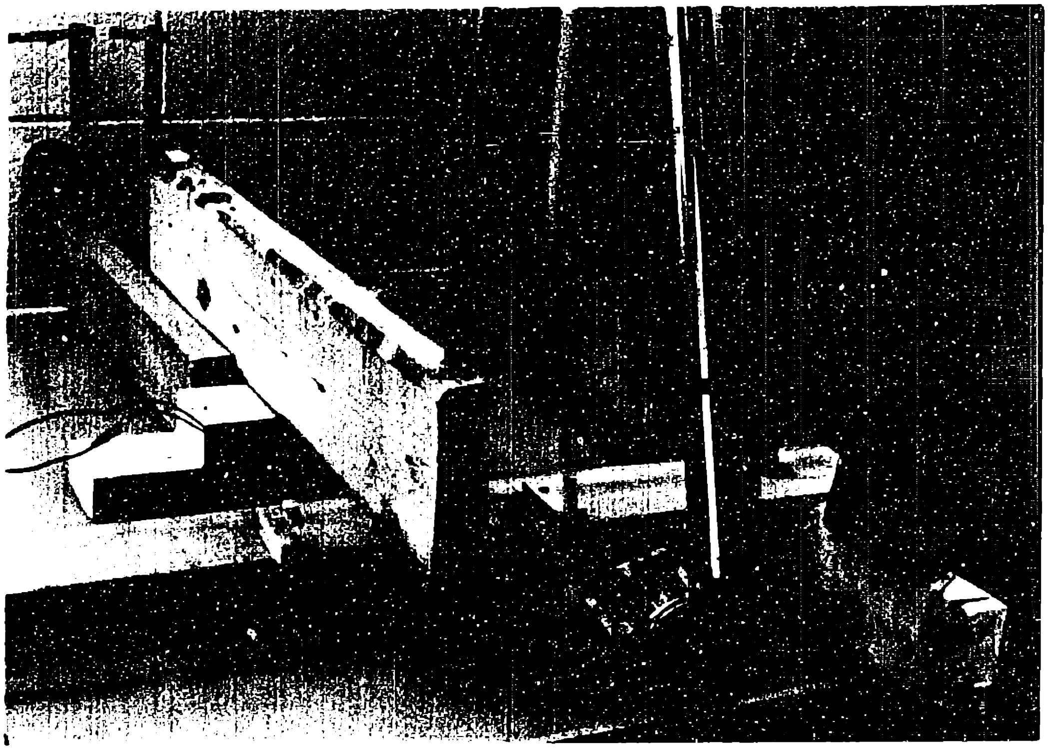

Figure 43 - Task Board for Presence of Object Contact Force Experiments

Two identical objects were placed in the remote environment. The objects were 0.75 inch squares and a fsr was placed on each object to detect forces when using the auditory or vibrotactile displays. The objects were made of wood, were fixed in place, and projected outwards from a base toward the camera viewpoint. Figure 43 shows the task board with the E2 during performance of the task.

Since the base and the objects were fixed, the magnitude of the force applied to the target was irrelevant. A 0.75 inch square peg was placed in the gripper of the E2. The subjects tapped each object with the tip of the E2 gripper alternating between the two objects for fifteen seconds, and the number of taps were recorded. At the start of each fifteen second trial, the E2 was in contact with a plate attached to a microswitch. When a subject moved the E2 away from the plate to start a trial, the microswitch was released and the timer would start. Two of these plates were used, one to the left of the task board and one to the right. This enabled the subjects to alternate between starting positions to the left and to the right of the objects. After fifteen seconds a buzzer would sound indicating the end of the trial. The subjects were instructed to tap between each object as quickly as possible, but contact had to be made with each object in order for a tap to be recorded. The view provided via the television monitor was clear. Knowing when contact was made and reacting quickly was the key to successful performance. Therefore force information would be helpful to the operator by providing a cue as to when object contact was present.

Four feedback scenarios were used: 1) force feedback through bilateral master-slave force feedback plus a visual display of the task, 2) sensory substitution of force feedback through vibrotactile displays on the tips of the subject's index finger and thumb plus a visual display of the task, 3) sensory substitution of force feedback through the auditory display plus a visual display of the task, and 4) a visual display of the task without any force feedback information. A clear television view was always provided to the subject.

To provide traditional bilateral master-slave force feedback, the force feedback capability of the E-2 was used. Only the degree of freedom perpendicular to the surface of the objects, i.e. straight ahead from the subject, was enabled so that the only force presented bilaterally to the operator was that of contact on the objects. Both the vibrotactile and auditory displays operated in on-off mode: when no contact force at the tip of the manipulator was present, no vibration or sound was present. When any contact was made at the tip of the manipulator, a high intensity vibration or sound was presented to the subject independent of the magnitude of the contact force. The auditory display presented an auditory signal at 1000 Hz to both ears simultaneously at high intensity whenever contact was made with a target object. When the vibrotactile display was used a 250 Hz vibratory signal of high intensity was presented simultaneously through two vibrators, one located on the subject's index finger and one on the thumb. The intensity was constant and independent of the magnitude of the force since only the presence of the force was of interest.

Four test subjects were used, providing for a balanced latin square experimental design where each of the four experimental conditions preceded and followed each of the other experimental conditions an equal number of times. Each subject was trained and given warm-up time prior to the experimental trials. Six trials were conducted for each experimental condition by each subject.

Table 6 and Figure 44 display the experimental results for the presence of contact force experiments.

Force Feedback Condition	Mean Number of Taps	Standard Deviation
No Force Feedback	20.4	4.52
Traditional Force Feedback	23.2	3.83
Vibrotactile Display	26.6	7.6
Auditory Display	29.0	7.96

Table 6 - Results for Presence of Contact Force Experiments

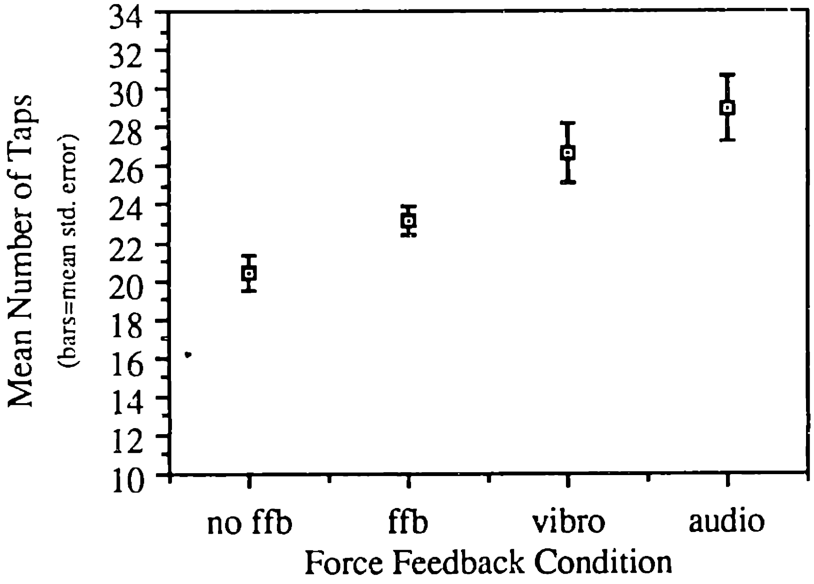

Figure 44 - Results for Presence of Contact Force Experiments

A series of paired t-tests were performed on the data. The results show that the auditory (t(23)=4.75,p<0.001) and the vibrotactile (t(23)=3.66,p<0.001) displays as well as traditional force force feedback (t(23)=5.61, p<0.001) provided a significant advantage over the no force feedback condition. The auditory display ($t(23)=3.9, p<0.001$) and the vibrotactile display ($t(23)=2.52, p<0.02$) provided a significant performance improvement over traditional force feedback. Finally the auditory display produced significantly better performance than the vibrotactile display ($t(23)=3.75, p<0.001$).

These experimental results were probably closely linked with reaction time since the subject was required to recognize a stimulus and react as quickly as possible. Recognizing the presence of a contact force and reacting appropriately was quickest with the auditory display, less quick with the vibrotactile display, slower with traditional force feedback, and slowest with a visual display alone and no force feedback. Chapters 9 and 10 present detailed analyses of these results.

5.2 Magnitude of Contact Force

The objective of these tasks was to test the representation of the magnitude of a contact force through sensory substitution. Applications for these experiments include a telemanipulation task where a maximum contact force level exists, above which damage and task failure will occur. Two target objects 0.75 inches square were again used as described in section 5.1, however now the objects were attached to moveable bases as opposed to a fixed base. In addition, weights could be added to the bases to alter the amount of force that would move the objects due to varying frictional resistances. Figure 45 shows the task board arrangement.

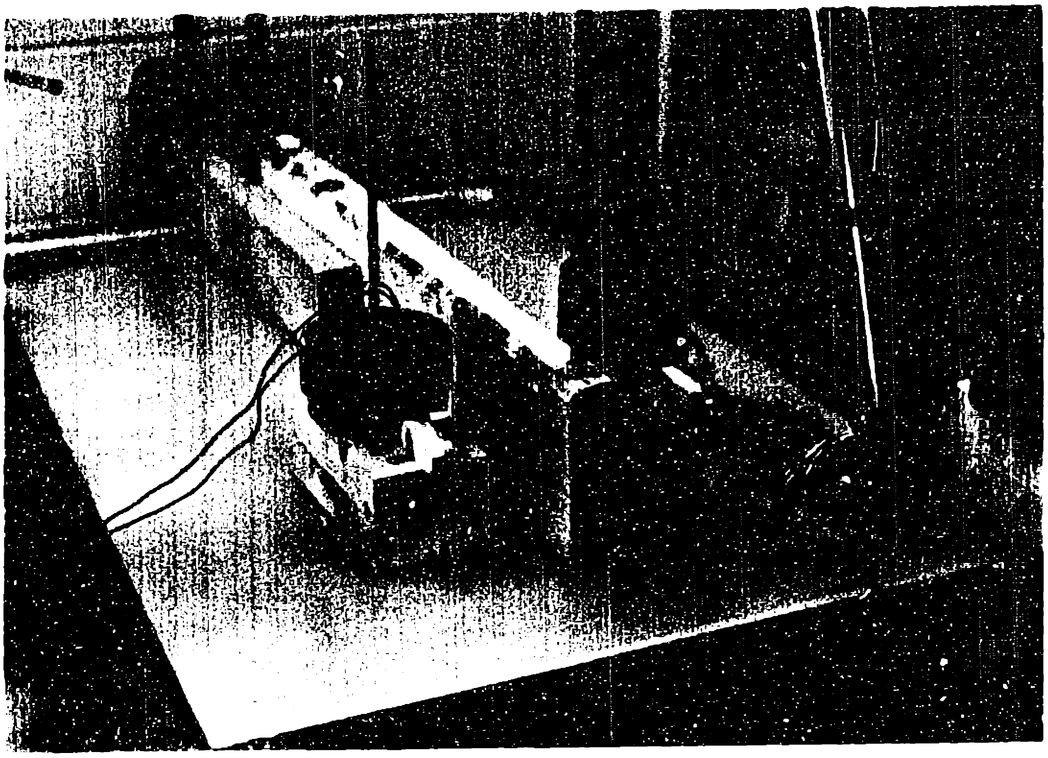

Figure 45 - Task Board for Magnitude of Object Contact Force Experiments

The subjects were instructed to make contact between the two objects as quickly as possible for fifteen seconds in a similar manner as that described in section 5.1. The task began when the subject moved the E2 away from the microswitch which started the timer and ended when the buzzer sounded after fifteen seconds. The number of taps was recorded, however now the blocks could move and for every 0.25 inches of displacement, a penalty of one tap was subtracted from the total for that trial (total number of taps - penalty taps = adjusted number of taps). Therefore the magnitude of the force being exerted now became important, since the adjusted number of taps was the criterion upon which performance results were analyzed.

Four force feedback conditions were used: 1) traditional bilateral master-slave force reflection, 2) sensory substitution of force feedback through the vibrotactile display, 3) sensory substitution of force feedback through the auditory display, and 4) no force information. The view for these experiments through the television monitor was again clear and identical for each feedback condition. Four trained test subjects were tested to provide for a balanced latin square experimental design. Six trials were run for each condition by each subject.

Two different weight levels yielding two different force ranges for movement were used. The lower level permitted a force range of 0 to 0.5 pounds before movement would occur. The higher level allowed a force range of 0 to 2 pounds before movement would occur. The maximum amount of force for the task that could be exerted with the manipulator was approximately 10 pounds. The subjects were trained so that they understood and could recognize the different acceptable force ranges. They were also given practice trials so that they could develop strategies to balance the tradeoff between speed and penalty in order to maximize their adjusted number of taps score.

A force sensing resistor was located on each object to measure forces when the auditory or vibrotactile displays were used. The auditory display simultaneously presented a single 1000 Hz auditory signal to both ears, and the loudness of the tone was proportional to the magnitude of the force. The auditory-force relationship used was auditory loudness function described previously in sections 3.3.1 and 3.3.2 for y-direction forces. The vibrotactile display simultaneously presented identical 250 Hz vibrotactile stimuli to the index finger and thumb, with vibration magnitude scaled to force. The vibrotactile-force relationship used was developed from the sensory magnitude functions discussed in sections 3.4.2 and 3.4.3 for y-direction forces. To provide traditional bilateral master-slave force feedback, the force feedback capability of the E-2 was used. Only the degree of freedom perpendicular to the surface of the objects, i.e. straight ahead from the subject (y-direction), was enabled so that the only force presented bilaterally to the operator was that of contact on the objects.

The experimental results are listed in table 7 for the higher (0 - 2 lbs) force range, and in table 8 for the lower (0 - 0.5 lbs.) force range. The mean total number of taps made, the mean penalty taps assessed due to undesirable movement, and the mean adjusted number of taps made (total - penalty) are shown along with their standard deviations in parentheses.

Force Feedback Condition	Mean Number of Total Taps	Mean Penalty Taps Assessed	Mean Adjusted Number of Taps
No Force Feedback	9.71 (3.53)	2.58 (1.84)	7.13 (3.53)
Traditional Force Feedback	13.8 (2.44)	1.54 (1.29)	12.3 (2.61)
Vibrotactile Display	15.1 (4.31)	0.833 (1.17)	14.3 (4.03)
Auditory Display	17.1 (4.61)	0.958 (1.23)	16.13 (4.76)

Table 7 - Results for Magnitude of Object Contact Force Experiments
Higher Force Range (0-2 lbs.)
(standard deviations in parentheses)

Force Feedback Condition	Mean Number of Total Taps	Mean Penalty Taps Assessed	Mean Adjusted Number of Taps
No Force Feedback	7.08 (2.06)	6.67 (3.2)	0.417 (2.32)
Traditional Force Feedback	9.00 (2.7)	1.79 (0.932)	7.21 (1.72)
Vibrotactile Display	10.6 (3.2)	3.5 (1.75)	7.13 (2.82)
Auditory Display	9.92 (2.78)	2.13 (1.15)	7.79 (3.2)

Table 8 - Results for Magnitude of Object Contact Force Experiments
Lower Force Range (0-0.5 lbs.)
(standard deviations in parentheses)

Figure 46 displays the results for the magnitude of contact force experiments for the two force ranges tested. The data points represent the mean adjusted number of taps (total - penalty), which was the score that the test subjects were trying to maximize.

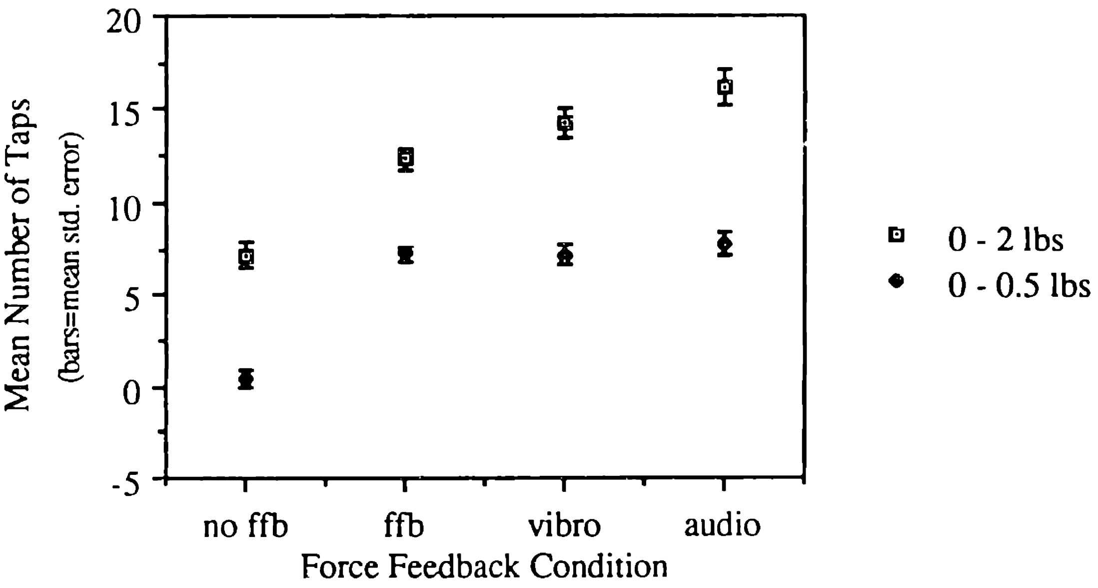

Figure 46 - Results for Magnitude of Object Contact Force Experiments

A series of paired t-tests were performed and indicated that at the higher force range the auditory display (t(23)=8.42,p<0.001), the vibrotactile display (t(23)=10.71,p<0.001), and traditional force feedback (t(23)=7.42,p<0.001) all produced significant performance advantages over using the television monitor without any force information. Further, the auditory display (t(23)=4.6,p<0.001) and the vibrotactile display (t(23)=3.18,p<0.005) provided a significant improvement in performance over traditional force feedback. In addition the auditory display produced a significant advantage over the vibrotactile display (t(23)=2.69,p<0.015). These results for the higher force range are similar to the results obtained for the presence of contact when the object was fixed and the force range was unlimited. It appears that the higher force range was sufficiently high so that the operator was able to concentrate on the speed of movement, overcome the penalty assessed, and obtain similar performance to that observed in the presence of contact force experiments. Therefore, these results, like those for the presence of contact force experiments, were probably most closely linked with reaction time.

Different results were obtained for the lower force range. The auditory display (t(23)=7.88,p<0.001), vibrotactile display (t(23)=9.15,p<0.001), and traditional force feedback (t(23)=13.39,p<0.001) again yielded superior performance when compared to manipulation using the television monitor alone. However, there were no significant differences between the vibrotactile display, the auditory display, and traditional force feedback. When comparing the results obtained at the lower force range against those at the higher force range, the higher force range had a significantly greater number of taps for each feedback condition.

In order to look deeper into the results for the higher and lower force ranges, the data on the total number of taps without penalty and the data on the penalty taps assessed were also analyzed. Figure 47 displays the results for the total number of taps.

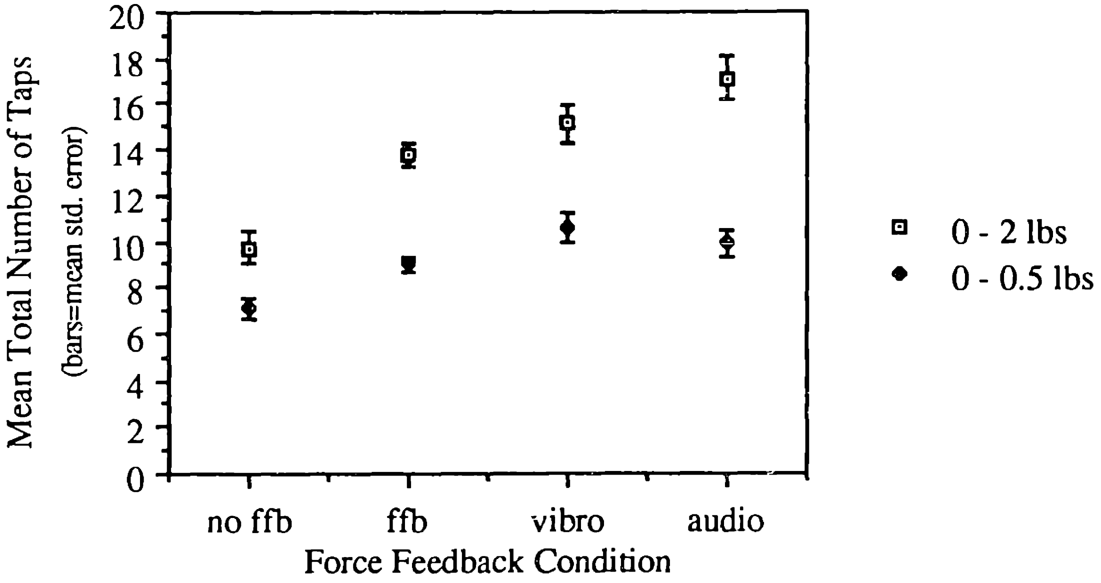

Figure 47 - Mean Total Number of Taps for Magnitude of Contact Force Experiments

The statistical analysis performed on the data summarized in figure 47 showed that at the higher force range the auditory display (t(23)=7.85,p<0.001), vibrotactile display (t(23)=9.34,p<0.001), and traditional force feedback (t(23)=5.91,p<0.001) all produced significantly more total number of taps than did the no force feedback case. When comparing sensory substitution to traditional force feedback, only the auditory display (t(23)=3.88,p<.001) provided a significantly higher total number of taps than traditional force feedback. Further, the auditory display (t(23)=2.63,p<0.015) produced significantly more total number of taps than did the vibrotactile display.

For the lower force range, the auditory display (t(23)=4.84,p<0.001), vibrotactile display (t(23)=6.84,p<0.001), and traditional force feedback (t(23)=3.34,p<0.003) all produced significantly more total number of taps than did the no force feedback case. There were no significant differences in the mean total number of taps between the vibrotactile display, the auditory display, and traditional force feedback. When comparing the higher force range to the lower force range for each individual feedback option, the higher force range always had a significantly greater number of total taps.

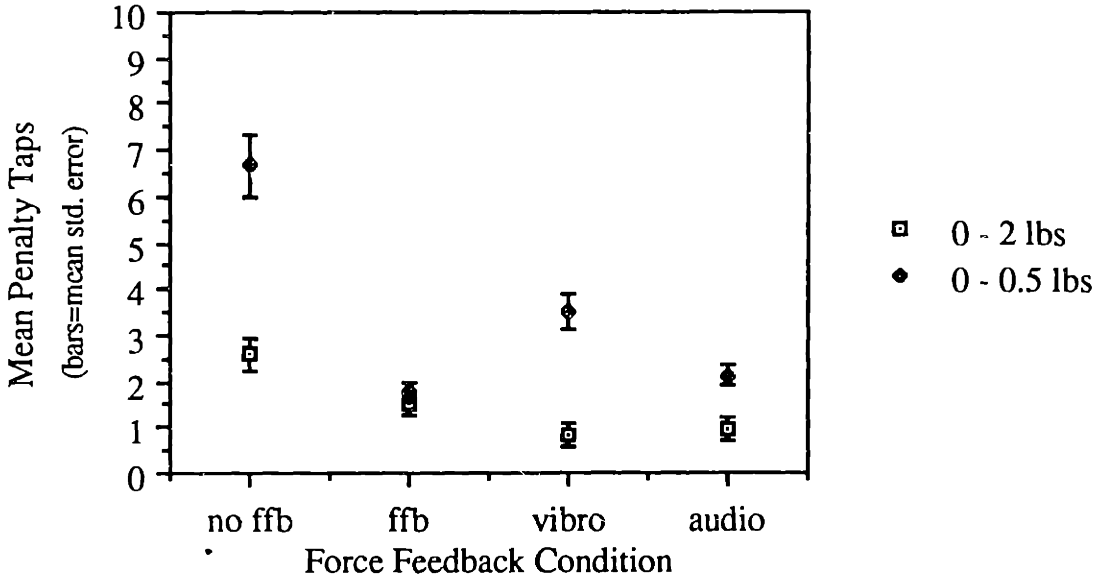

Figure 48 - Penalty Assessed for Magnitude of Contact Force Experiments

The data for the average penalty assessed for each feedback condition is shown in Figure 48. For the higher force range when using no force feedback, a significantly greater amount of penalty was assessed when compared to all three force display options: auditory display (t(23)=3.33,p<0.003), vibrotactile display (t(23)=3.81,p<0.001), traditional force feedback (t(23)=2.13,p<0.05). The only other significant difference was that force feedback had significantly more penalty that the vibrotactile display (t(23)=2.21,p<0.04). Therefore although the total # of taps between using traditional force feedback and the vibrotactile display were not significantly different, the greater penalty assessed when using traditional force feedback provided the vibrotactile display with a significant advantage when comparing the adjusted number of taps score.

For the lower force range when using no force feedback, a significantly greater amount of penalty was assessed when compared to all three force display options: auditory display ($t(23)=6.54, p<0.001$), vibrotactile display ($t(23)=4.26, p<0.001$), traditional force feedback ($t(23)=7.17, p<0.001$). In addition, the vibrotactile display produced significantly more error than either traditional force feedback ($t(23)=4.21, p<0.001$) or the auditory display ($t(23)=3.87, p<0.001$). Despite this result for the vibrotactile display, the penalty assessed was not enough to make a significant difference in the overall performance result concerning the adjusted number of taps. Further, the penalty always accounted for a significant difference in the overall performance, i.e., when analyzing the total number of taps before penalty versus the total number of taps after the penalty was assessed, there was a significant difference for each feedback condition and force range.

These differences between the results for the higher and lower force ranges are analyzed further in chapters 9 and 10.

5.3 Sustained Contact Force

These experiments focused on presenting information on the magnitude of a force that needs to be maintained over a period of time. The objective of this task is to measure how well a subject can establish and maintain a specific force using sensory substitution of force feedback. Applications for these experiments include a telemanipulation task where a force must be exerted over a period of time, and has a maximum level above which damage and task failure will occur.

Similar to the tests described in section 5.2, two objects 0.75 inches square with fsr's on the front were used to detect forces when using the auditory and vibrotactile displays. The objects were moveable, the television view was clear, and two different force ranges (0 to 0.5 lbs. and 0 to 2.0 lbs.) were tested. The task board was the same as that used for the magnitude of contact force experiments and is shown in figure 45.

However for these experiments the subjects were instructed to make alternating contact with each object and maintain that contact for three seconds. Force information was important in this case in order to tell the subject when contact had been established, if it was in the acceptable range so as not to move the object and incur a penalty, and whether the contact was constant so that continuous contact for the full three seconds was possible. Sustained contact for three seconds was indicated to the subject by a contact light. Four consecutive successful sustained contacts constituted a trial. Task time was recorded, with a five second add-on penalty for every 0.25 inches (or 2.5 seconds for every 0.125 inches) of object displacement. The task began when the E2 was lifted off from making contact with a microswitch that would start the clock. The task ended when the fourth contact light lit up and the clock was stopped. The trials alternated starting from the left and right of the target objects.

Four force feedback conditions (auditory sensory substitution, vibrotactile sensory substitution, traditional force reflection, and no force information), four trained test subjects, and six trials per condition per subject were used. The auditory display simultaneously presented a single 1000 Hz auditory signal to both ears, and the loudness of the tone was proportional to the magnitude of the force. The vibrotactile display simultaneously presented identical 250 Hz vibrotactile stimuli to the index finger and thumb, with vibration magnitude scaled to force. To provide traditional bilateral master-slave force feedback, the force feedback capability of the E-2 was used. Before the training and experiments were conducted, the subjects were instructed on the objective of the task and the tradeoff between fast task time and the penalties for displacing the objects. The subjects were then trained and given practice in order to better recognize the allowable force ranges track the changes in the contact forces with the different display options.

The experimental results for the higher (0 - 2 lbs) force range are listed in table 9, and table 10 lists the results for the lower (0 - 0.5 lbs.) force range. The mean unadjusted task time, the mean penalty time assessed due to undesirable movement, and the mean adjusted task time (unadjusted time + penalty time) are shown along with their standard deviations in parentheses.

Force Feedback Condition	Unadjusted Task Performance Time	Mean Penalty Time Assessed	Mean Adjusted Task Time
No Force Feedback	22.1 (2.92)	5.42 (6.9)	27.5 (8.46)
Traditional Force Feedback	19.7 (2.11)	0.52 (1.04)	20.2 (2.29)
Vibrotactile Display	19.6 (1.46)	0.1 (0.51)	19.7 (1.41)
Auditory Display	20.3 (2.34)	0.1 (0.51)	20.4 (2.25)

Table 9 - Results for Sustained Object Contact Force Experiments
Higher Force Range (0-2 lbs.)
(standard deviations in parentheses)

Force Feedback Condition	Unadjusted Task Performance Time	Mean Penalty Time Assessed	Mean Adjusted Task Time
No Force Feedback	28.2 (5.99)	14.4 (5.82)	42.5 (9.58)
Traditional Force Feedback	25.6 (5.74)	3.23 (3.34)	28.8 (7.44)
Vibrotactile Display	24.7 (2.63)	4.48 (3.4)	29.2 (5.51)
Auditory Display	24.6 (3.34)	3.23 (3.17)	27.8 (4.21)

Table 10 - Results for Sustained Object Contact Force Experiments
Lower Force Range (0-0.5 lbs.)
(standard deviations in parentheses)

The results for the sustained object contact force experiments are shown graphically in figure 49 for both of the tested force ranges. The data points represent the mean adjusted task times (total task time + penalty time), which was the score that the test subjects were trying to minimize.

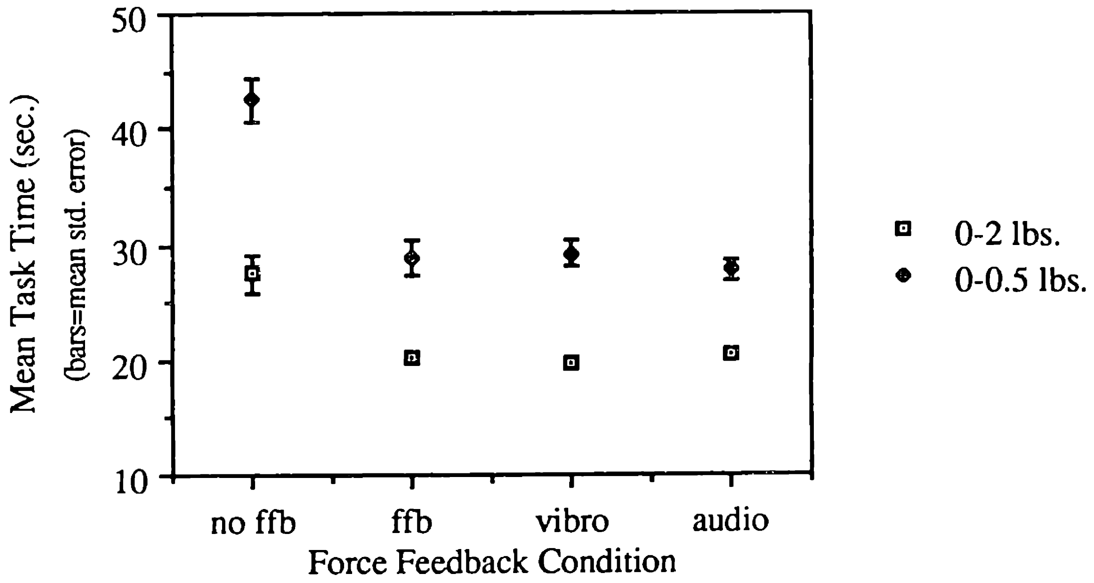

Figure 49 - Results for Sustained Object Contact Force Experiments

At the higher force range a significant improvement was present with the auditory display (t(23)=4.47,p<0.001), the vibrotactile display (t(23)=4.93,p<0.001), and traditional force feedback (t(23)=4.94,p<0.001) when compared to no force information. There were no significant differences between any other of the force feedback conditions.

For the experiments conducted at the lower force range (0 to 0.5 pounds), the auditory display (t(23)=7.2,p<0.001), vibrotactile display (t(23)=6.16,p<0.001), and traditional force feedback (t(23)=6.89,p<0.001) all had significantly lower task times than performing the task without any form of force feedback. There again were no significant differences between the two sensory substitution displays and traditional force feedback. In addition, the higher force range had significantly lower task times than the lower force range for each force feedback condition.

The data on the unadjusted task times and on the penalty times were also analyzed. Figure 50 displays the results for the mean unadjusted task times.

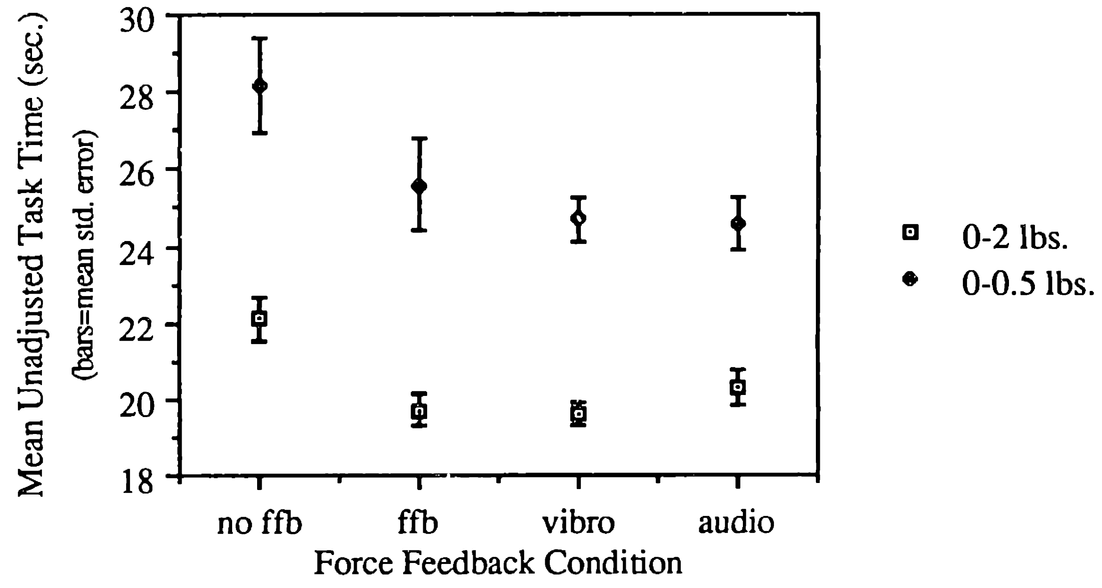

Figure 50 - Mean Unadjusted Task Times for Sustained Object Contact Experiments

Further analysis of the data in figure 50 showed that at the higher force range, the auditory display (t(23)=2.96,p<0.007), vibrotactile display (t(23)=5.02,p<0.001), and traditional force feedback (t(23)=4.52,p<0.001) all had significantly lower unadjusted task times when compared to having no force information. Further, the auditory display (t(23)=2.16,p<0.041) had a significantly higher mean unadjusted task time when compared to the vibrotactile display, although this did not affect the overall adjusted task time performance which found no significant difference between the two display options.

When analyzing the lower force range unadjusted task time data, the auditory display (t(23)=3.67,p<0.001), vibrotactile display (t(23)=3.19,p<0.004), and traditional force feedback (t(23)=2.26,p<0.033) all had significantly lower unadjusted task times than did the no force feedback scenario. No other significant differences were found to exist within the lower force range. As was expected, the lower force range produced significantly higher unadjusted task times than the higher force range for all of the force feedback conditions.

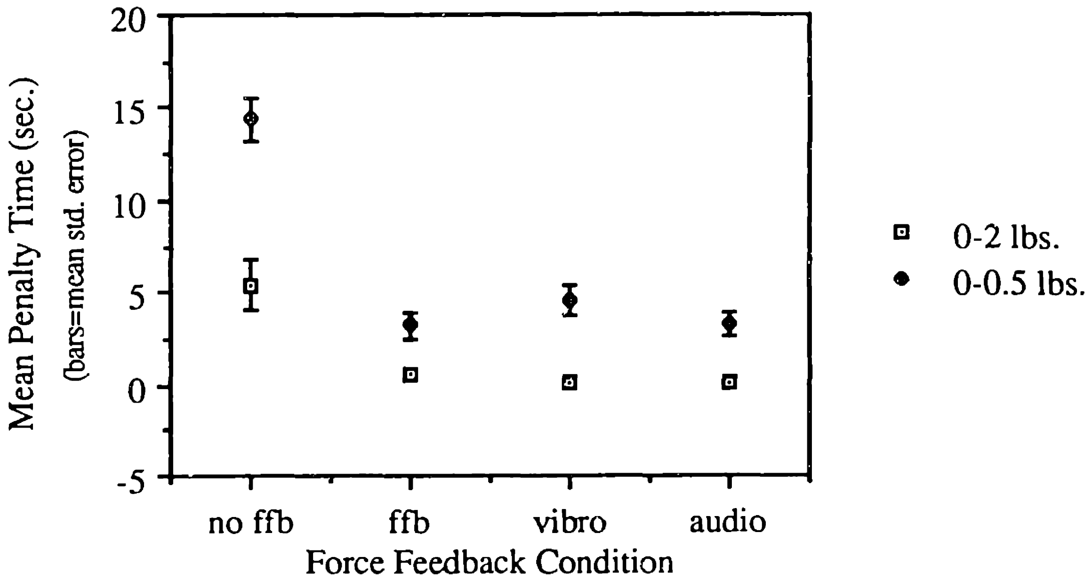

Figure 51 - Mean Penalty Times for Sustained Object Contact Experiments

The mean penalty times are shown graphically in figure 51. At the higher force range using no force information resulted in significantly more penalty time than using the auditory display (t(23)=3.74 p<0.001), vibrotactile display (t(23)=3.74,p<0.001), and traditional force feedback (t(23)=3.4,p<0.002). In addition, force feedback (t(23)=2.15,p<0.043) incurred significantly more penalty time than using the vibrotactile display. This significant difference did not however have an effect on the overall results since performance with traditional force feedback and with the vibrotactile display were found to be similar when analyzing the unadjusted and adjusted task times.

When considering the penalty assessed for the lower force range, the no force information case again incurred significantly more penalty than the auditory display (t(23)=7.94,p<0.001), vibrotactile display (t(23)=6.5,p<0.001), and traditional force feedback (t(23)=7.73,p<0.001). No other significant findings occurred for penalty time at the lower force level. A significantly greater amount of penalty was accumulated at the lower force range versus the higher force range for all the conditions tested.

6. MEASURING THE CAPABILITIES FOR COMMON MANIPULATION TASKS THROUGH PEG-IN-HOLE EXPERIMENTS

The sensory substitution displays were tested for their effectiveness for two types of peg-in-hole tasks: 1) a two sided hole (or slot), and 2) a four sided hole. Task time was used as the performance measure. These two types of holes were used to test sensory substitution force representations for relatively simple (two sided) and more complex (four sided) peg-in-hole tasks.

In addition, the tasks were conducted with both clear and obstructed views. The obstructed view was tested for two reasons. First, it has been shown in previous studies that force information can become more valuable to the operator of a teleoperated system when the visual feedback becomes degraded in some way [Massimino, 1988]. In addition, in many space teleoperation tasks, a clear view of the worksite is not always possible, either by direct vision or with a camera view [Pelletier, 1991]. Therefore an obstructed view is a situation that is likely to occur during actual space teleoperation tasks.

6.1 Peg-In-Hole Experiments with a Two Sided Hole

Schematic drawings of the task board for the peg-in-hole experiments with the two sided hole are shown in figure 52 (front view) and in figure 53 (side view of the hole). The peg dimensions are displayed in figure 54.

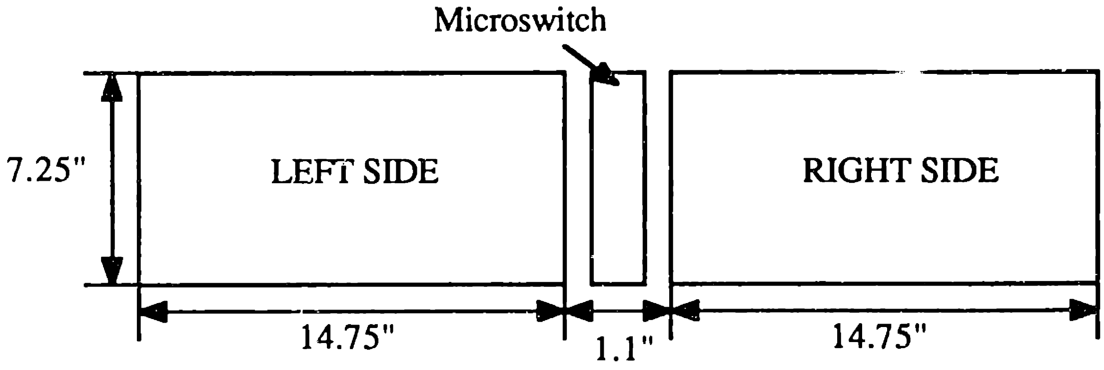

Figure 52 - Front View of the Task Board for the Peg-In-Hole Experiments with a Two Sided Hole

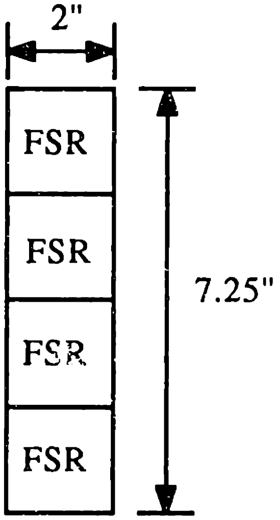

Figure 53 - Side View of the Hole for the Peg-In-Hole Experiments
with a Two Sided Hole

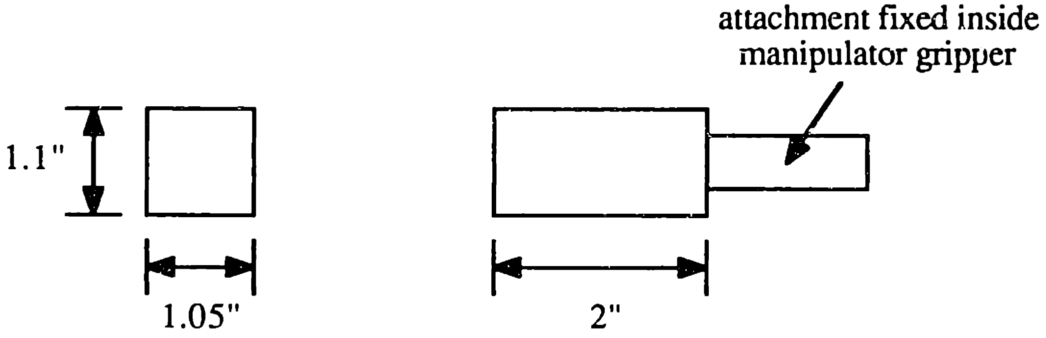

Figure 54 - Dimensions of the Peg Used for the Peg-In-Hole Experiments
Front View (shown on left) and Side View (shown on right)

The two sided hole was 1.1 inches wide (x-direction), 7.25 inches high (y-direction) and 2.0 inches deep (z-direction). Movement was constrained in the x-direction (side to side), and virtually unconstrained in the y-direction (up and down) when inserting the peg into the hole. The peg was fixed in the E2 gripper, was 1.1 inches in height, 1.05 inches wide, and two inches long. Two inches in length refers to the length of the peg sticking out from the gripper after the peg was fixed inside of the gripper (see figure 54). Therefore there was a tolerance of 0.05 inches in the x-direction and a very large tolerance in the y-direction. The two sided hole required that the entire length of the peg (2 inches) be inserted to complete the task. This required the operators to not only recognize when an edge of the hole was located, but also to manipulate the peg entirely into the tight fitting hole by identifying the forces being exerted on each of the two sides of hole.

The sensory substitution displays now had to be designed to display multiple force presentations. The key forces to be presented were: 1) the force on the right side of the hole, 2) the force on the left side of the hole, and 3) the force being exerted on the peg. The forces on the two sides of the hole were important to inform the operator that contact had been made with an edge of the hole, and to help the human operator determine the magnitude of these forces in order to complete the task. The force on the peg was useful because it indicated to the operator when the peg was in contact with the remote environment surrounding the hole.

For the auditory display, a combination of pitch discrimination and localization was used to represent the three key forces. Combining these two auditory dimensions gives a multidimensional representation of the different force positions. This method was chosen because the channel capacity of the human operator is increased with multidimensional stimulus presentations (pitch and localization combinations) compared to unidimensional presentations (pitch or localization independently) [Pollack, 1953]. The force on the right side of the hole was presented as a medium pitch (1000 Hz) tone to the right ear only. A medium pitch (1000 Hz) tone to the left ear alone represented the force on the left side. The force on the peg was presented as a very low pitch (28 Hz) tone to both ears, which made the tone appear to the subjects as emanating from the middle of the head. The loudness of each tone was related to the magnitude of the appropriate forces (see section 3.3.2 for details).

When using the vibrotactile display, vibrators placed at sensitive skin locations represented the different forces. The fingertips and the palm of the hand were selected as the locations for the vibrators for the peg-in-hole experiments because these regions are the most sensitive, i.e., have the lowest threshold, to vibratory stimuli in the 250 Hz range

[Wilska, 1954]. Further, while developing some of the early tactile displays that were used in their experiments, Hill, Bliss, and Gardner [1970] noted that vibrators attached to the fingers and hands successfully provided task information to the operator. Bliss, Hill, and Wilber [1971] made design recommendations for the manipulator sensors and the tactile displays based on their research results. They found that the tactile stimulators produced the best results when mounted on corresponding parts of the operator's hand, specifically the thumb, fingertip, finger, and wrist.

In addition, these skin locations made it easy for the test subjects to interpret the stimuli and identify the location of the force. For example, the force on the right side of the hole was presented as a vibration from a vibrator in contact with the index finger. When holding the E2 hand controller to perform the task, the operator's index finger was extended out and pointing toward the hole during insertion (see figure 45, chapter 3). Therefore the position of the index finger was on the right side of the master hand controller and corresponded to the location of the right side of the hole. A force on the right side of the hole would then be felt on the fingertip on the right side of the hand controller, making it more natural for the subjects to recognize the force position. A vibrator on the thumb represented the force on the left side, since the thumb position corresponded well to the left side of the hole. The force on the peg was presented as a vibration on the wrist. Each vibrator vibrated at 250 Hz, and the magnitude of the vibration was scaled to the magnitude of the associated force (see section 3.4.3 for details).

The task would start with the test subject moving the E2 slave arm away from a microswitch which would start a clock, and ended when the peg was inserted into the hole and made contact with another microswitch which would stop the clock. In addition, a contact light attached to the video monitor in front of the test subject would light up indicating to the subject that the peg was fully in the hole and the task was completed. The task time would then be recorded, and a new trial would be performed. Two microswitches could start the clock, one on the left side of the task board, and one on the right side of the task board. The subjects would alternate starting the tasks from each of the two microswitches to give alternating right and left starting points. Each side of the hole was two inches deep, and four force sensing resistors were placed on each side (see figure 53) to detect forces on the right and left sides of the hole when using the sensory substitution displays. A force sensing resistor was also placed on the tip of the peg in order to measure the force exerted by the peg on the task board.

Four trained test subjects performed the tasks. They were trained by first performing the tasks informally to gain some familiarity. Then practice trials were conducted and practice trial times were recorded, until the learning curves appeared to have flattened and performance was stable. On average, training for each task took approximately one to two hours for each subject. A counterbalanced experimental design was used to balance the effects of learning and fatigue during the experimental trials. Each subject performed ten trials for each experimental condition.

6.1.1 - Results for Two Sided Peg-In-Hole Experiments with a Clear View

The results for the experiments with a clear view are listed in table 11 and shown in figure 55. Four feedback conditions were tested: 1) using the visual feedback from the television monitor alone without any force information (labeled in figure 55 as "no ffb"), 2) combining visual feedback with traditional force feedback ("ffb"), 3) combining visual feedback with vibrotactile sensory substitution of force feedback ("vibro"), and 4) combining visual feedback with auditory sensory substitution of force feedback ("audio").

Feedback Condition	Mean Task Time (sec.)
No Force Feedback	3.73
Traditional Force Feedback	3.68
Vibrotactile Display of Sensory Substitution for Force Feedback	3.68
Auditory Display of Sensory Substitution for Force Feedback	3.64

Table 11 - Results for the Two Sided Peg-In-Hole Experiments with a Clear View

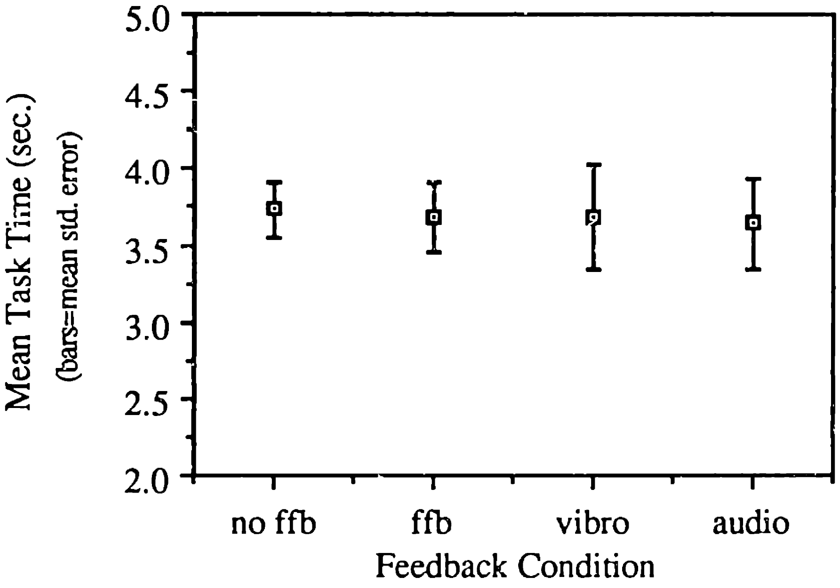

Figure 55 - Results for the Two Sided Peg-In-Hole Experiments with a Clear View

For the results shown in figure 55, there were no significant performance differences between any of the feedback conditions. Visual feedback alone ("no ffb") appears to have dominated and was sufficient by itself to allow the subjects to perform the task as quickly as possible, since adding any force information to the visual feedback did not have any impact on performance. These theories are investigated further in chapters 9 and 10.

6.1.2 - Results for Two Sided Peg-In-Hole Experiments with an Obstructed View

Different results than those presented in section 6.1.1 were obtained when the visual feedback was obstructed. When using a fully obstructed view, it was impossible to perform the task with visual feedback alone. Thus performing the task with an obstructed view forced the subjects to adopt very different task strategies, since they became totally dependent on force information in order to perform the task.

Therefore only three experimental conditions could be tested: 1) traditional force feedback, 2) vibrotactile sensory substitution of force feedback, and 3) auditory sensory substitution of force feedback. The results are shown in table 12 and figure 56.

Feedback Condition	Mean Task Time (sec.)
Traditional Force Feedback	4.26
Vibrotactile Display of Sensory Substitution for Force Feedback	5.5
Auditory Display of Sensory Substitution for Force Feedback	5.44

Table 12 - Results for the Two Sided Peg-In-Hole Experiments with an Obstructed View

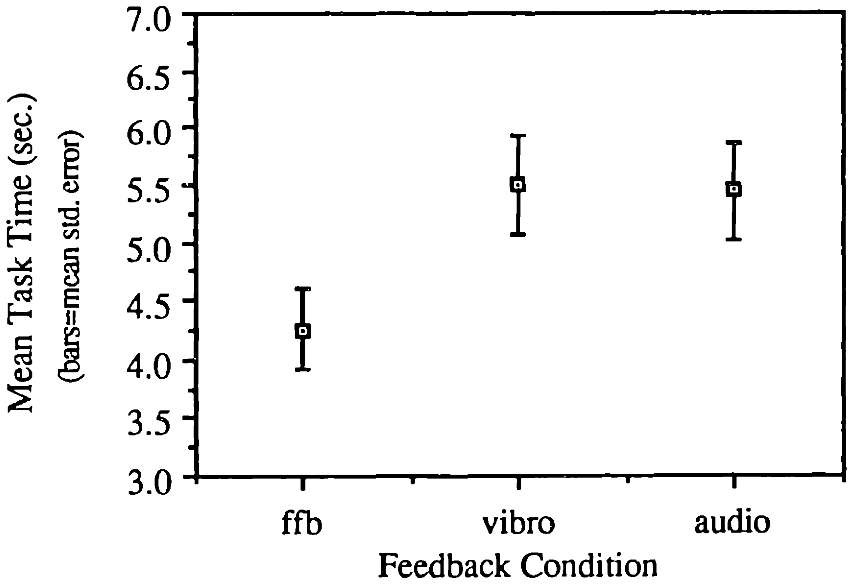

Figure 56 - Results for the Two Sided Peg-In-Hole Experiments with an Obstructed View

A series of paired t-tests showed that the mean task times with traditional force feedback were significantly lower than with either the vibrotactile display (t(23)=2.4,p<0.021) or the auditory display (t(23)=2.15,p<0.04). The advantage of traditional force feedback for this task is analyzed in chapter 10.

Most important was the demonstration that sensory substitution enabled the task to be completed successfully without any useful visual feedback, and with the operator relying entirely on one of the sensory substitution displays. For this type of task, therefore, if traditional force feedback were not available, and if vision became degraded or obstructed for short or long periods of time, the task could still be successfully completed by using sensory substitution.

6.2 Peg-In-Hole Experiments with a Four Sided Hole

A schematic drawing of the front view of the task board for the peg-in-hole experiments with the four sided hole is shown in figure 57. A side view of the hole is displayed in figure 58.

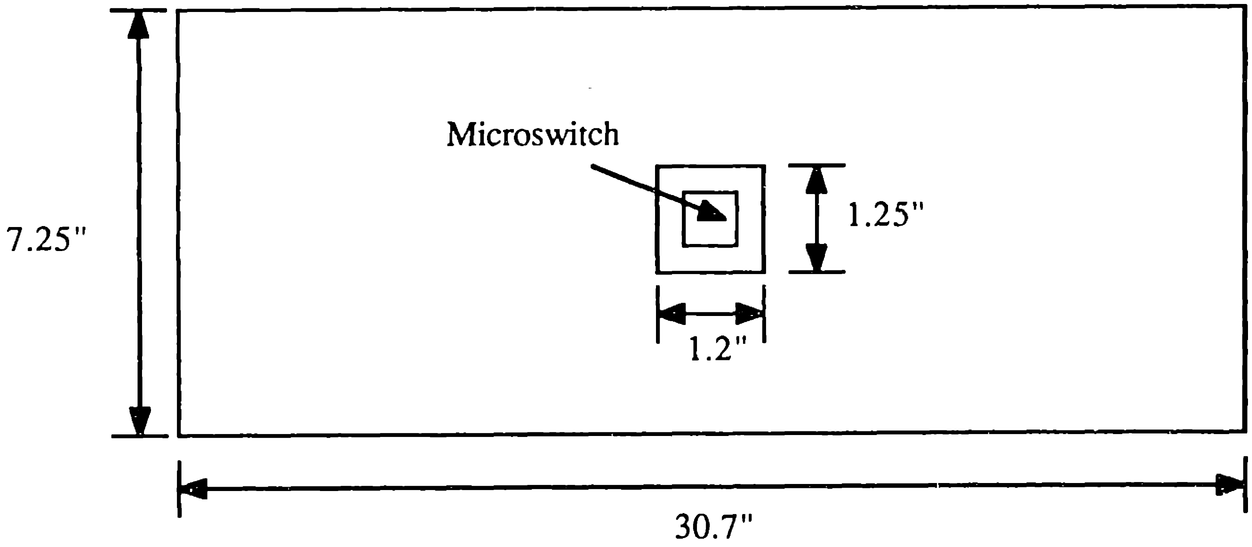

Figure 57 - Front View of the Task Board for the Peg-In-Hole Experiments with a Four Sided Hole

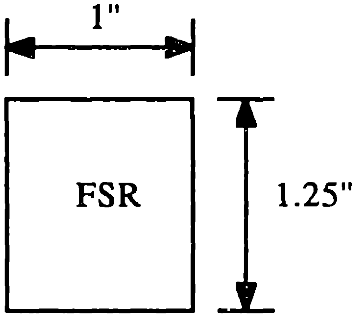

Figure 58 - Side View of the Hole for the Peg-In-Hole Experiments with a Four Sided Hole

The four sided hole was 1.2 inches wide (x-direction), 1.25 inches high (y-direction) and 1.0 inches deep (z-direction). Movement was constrained in both the x-direction (side to side), and in the y-direction (up and down) when inserting the peg into the four sided hole, as opposed to movement being constrained in only the x-direction for the previously discussed two sided hole. The same peg used in the two sided peg-in-hole experiments was used in the four sided peg-in-hole experiments (see figure 54). The peg was fixed in the E2 gripper, was 1.1 inches in height, 1.05 inches wide, and stuck out two inches in length from the gripper. Therefore there was a tolerance of 0.15 inches in the x-direction and 0.15 inches in the y-direction for inserting the peg into the four sided hole. The tolerance in the x-direction for the four sided hole was three times the tolerance in the x-direction for the two sided hole. Further, the four sided hole task required that only one half of the length of the peg (1 inch) be inserted into the hole in order to complete the task, whereas the two sided hole required that the entire length of the peg (2 inches) be inserted to complete the task. The constrained movement in both the x and y directions combined with the tight tolerances in each direction for the four sided hole, required the test subjects to recognize when the all edges of the hole had been contacted, and the relationships between those forces in order to finish the task.

The four sided hole peg-in-hole experiments required more complicated force presentations for the sensory substitution displays than did the two sided hole experiments, since more forces were important for successful performance. The key forces to be presented were now: 1) the force on the right side of the hole, 2) the force on the left side of the hole, 3) the force on the top side of the hole, 4) the force on the bottom side of the hole, and 5) the force being exerted on the peg. Presenting information on the forces on the four sides of the hole indicated to the operator when and where contact had been made with the hole, i.e., force direction information, and informed the operator of the magnitude of the contact force as well. The feedback concerning the magnitude of the force on the peg, informed the operator as to when the peg was in contact with the areas of the task board that surrounded the hole.

For the auditory display, a combination of pitch discrimination and localization was used to present the five key forces to the subjects. The force on the right side of the hole was presented as a medium pitch (1000 Hz) tone to the right ear only, and a medium pitch (1000 Hz) tone presented to the left ear only represented the force on the left side of the hole. The force on the top part of the hole was presented as a very high pitch (3500 Hz) tone to both ears which made the tone appear to the subjects as emanating from the middle of the head. The force on the bottom part of the hole was presented as a low pitch (350 Hz) tone to the middle of the head. The force on the peg was presented as a very low pitch (28 Hz) tone to the middle of the head. The locations of right, left, and middle of the head were chosen to make it easy for the subjects to identify the position of the force. The pitch of the tones were also selected to aid in position identification. For example, the high pitch tone corresponded to the top side and the low pitch tone corresponded to the bottom side. The spacing of the frequencies (pitches) to represent the forces was based on the results of the psychophysical experiments on absolute judgements (see section 4.1.4). This ensured that the subjects could easily and absolutely recognize where the force was being exerted. The loudness of each tone was again related to the magnitude of the appropriate forces.

An additional design consideration for the auditory display described above was the possible difference in perceived loudness of tones presented to one ear independently versus to both ears simultaneously. A sound presented to both ears can be perceived as being nearly twice as loud as sound presented to one ear [Scharf and Houtsma, 1986]. For pure tones, estimates have ranged from a ratio of 1.7 [Scharf and Fishken, 1970] to 2.0 [Marks, 1979]. If these relationships were not factored into the force presentations, then forces presented to one ear (right and left side forces) would be interpreted as being lower in magnitude than an equal force presented to the middle of the head (top and bottom side forces). Further, the frequency of a tone can also affect the perceived loudness of a tone. For example, a low pitch of approximately 500 Hz and 60 db SPL has been found to sound louder than a high pitch tone of 4000 Hz at 60 db SPL [Scharf, 1978]. Therefore the loudness of the tones that were presented to both ears (top and bottom side forces) and the loudness of the high pitch tone (top sided) were adjusted and tested. This was done to ensure that forces of equal magnitude appeared to the subjects as having the same loudness, independent of the location or pitch of the auditory cue representing the force.

When using the vibrotactile display the fingertips and the palm of the hand were selected as the locations for the vibrators. The force on the right side of the hole was presented as a vibration to the index finger, while vibrator on the thumb represented the force on the left side. The palm was utilized to represent forces on the top and bottom sides of the hole. For forces on the top side of the hole, a vibration was presented to the upper part of the palm. The force on the bottom side of the hole was represented as a vibration on the lower part of the palm. In addition to being sensitive skin locations, these positions made it easy for the subjects to correlate the positions of the forces acting on the upper and lower sides of the hole, because the force positions they represented clearly corresponded to the upper and lower areas on the palm. The force on the peg was again presented as a vibration on the wrist. Each vibrator vibrated at 250 Hz, and the magnitude of the vibration was scaled to the magnitude of the associated force.

6.2.1 Psychophysical Experiments for the Four Sided Peg-In-Hole Tasks

In order to test the sensory substitution representations of force described above for the four sided hole peg-in-hole experiments, an additional psychophysical experiment was conducted. A force vector was positioned at sixteen different locations on an imaginary square hole as shown in figure 59. The position of the vector was represented through the auditory and vibrotactile displays in separate experimental sessions.

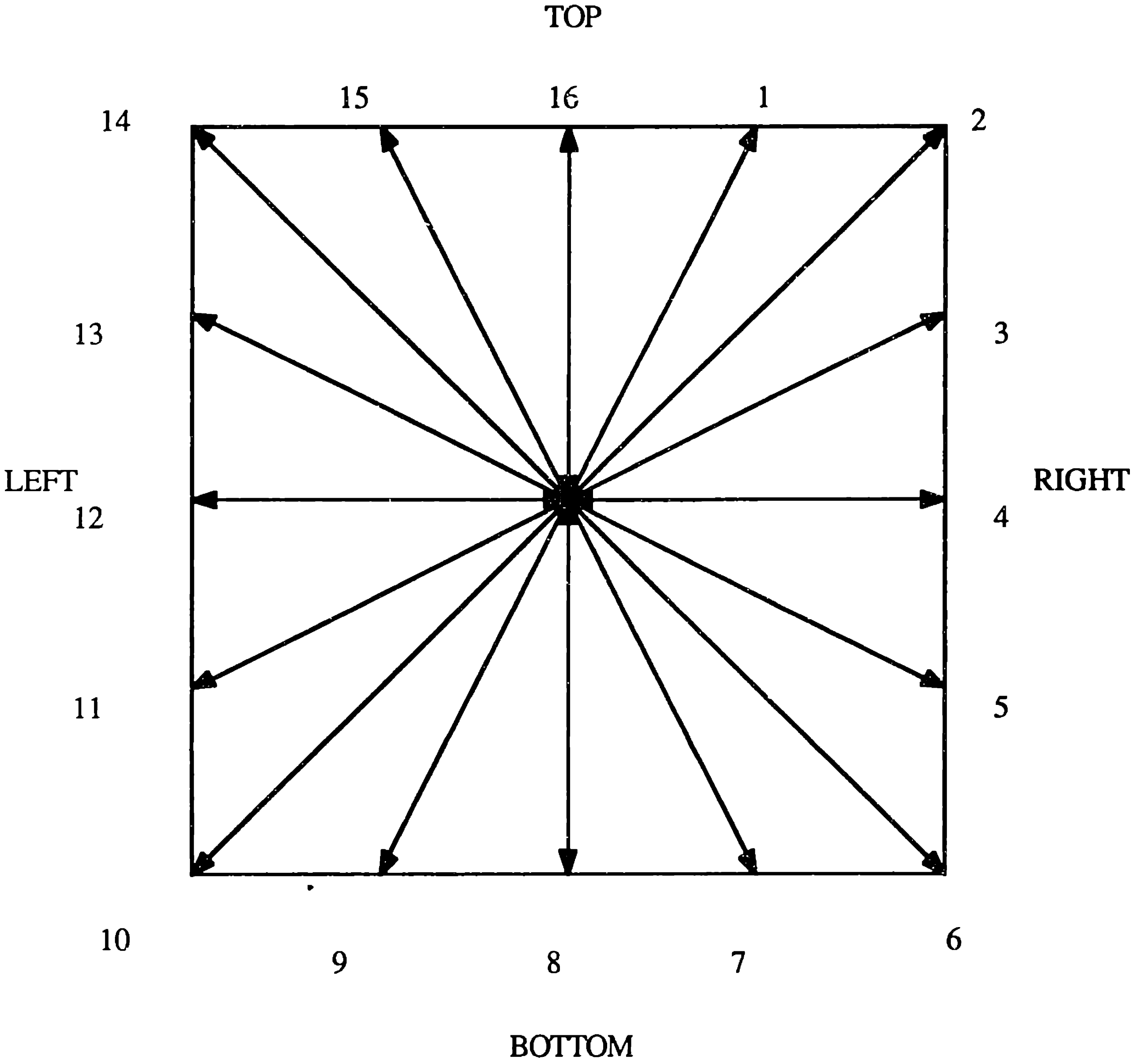

Figure 59 - Force Positions for the Peg-In-Hole Psychophysical Experiments

The subjects were given either the auditory or vibrotactile sensory substitution presentations of the force position, and then had to respond as to which of the sixteen positions was being represented. For example, if position 16 were presented with the auditory display, the subject would hear a single very loud high pitch (3500 Hz) tone to the middle of the head. If position 16 were presented through the vibrotactile display, a high intensity 250 Hz vibration would be presented to an area on the upper part of the palm. Another, more complicated example would be the representation of position 7. With the auditory display, position 7 would be presented as a combination of a low pitch (350 Hz) tone to the middle of head and a medium pitch (1000 Hz) tone to the right ear. The low pitch tone would have a greater loudness than the medium pitch tone, thus displaying the relative magnitudes of the force vector components and indicating the position of the force in the hole to the subjects. When testing the vibrotactile display, position 7 was represented as a combination of a 250 Hz vibration to the lower part of the palm and a 250 Hz vibration to the index fingertip. The vibration on the lower part of the palm would have a larger intensity than the vibration on the index fingertip, and this relationship would display the position of the force to the subject.

Four test subjects were trained for the psychophysical experiments, and became familiar with the different positions and their presentations through each display. A representation of the diagram shown in figure 59 was in front of the subjects during the experiments, to help them identify the different possible force positions. Practice sessions were conducted to provide additional training, and were identical to the experimental sessions. During the experimental sessions, each position was presented randomly five times per display for each subject. Therefore each subject completed eighty experimental trials for each display. Each stimulus was presented for two seconds. The subjects were required to attempt to identify which of the sixteen positions was being represented. The experiments were automated on the PC, and the subjects would input their responses and request the next stimulus at their own pace.

The experimental results were analyzed using three criteria: 1) exact force position, 2) force quadrant, and 3) dominant force. For the first criterion, exact force position, the total number of correct responses out of the eighty trials were calculated for each subject with each of the displays. This gave the correct response rate for the total number of responses, and a subject had to be able to correctly identify the exact position of the force in order to record a correct response.

The second criterion, force quadrant, measured the subjects' abilities to recognize the correct quadrant of the hole in which the force was acting. For this criterion, the force position diagram shown in figure 59 was divided into four quadrants: 1) position 16 to position 4, 2) position 4 to position 8, 3) position 8 to position 12, and 4) position 12 to position 16. The data was then analyzed to determine how well each subject was able to identify the correct quadrant, not the specific position, in which the force was being exerted. For example if the stimulus position was position 5, correctly identifying the quadrant would have included responses of positions 4 through 8. Therefore the quadrant identification criterion (criterion #2) required less resolution and less accuracy than identifying the exact force position criterion (criterion #1), and therefore was expected to produce higher correct response rates.

The third criterion, dominant force, measured the subjects' abilities to correctly recognize the dominant force component being present. In other words, for the component of the force vector which was greater than or equal to any other component, was the subject able to correctly recognize that component as being greater than or equal to any other component. For example, if position 7 was presented did the subject identify a force on the bottom side of the hole as being dominant, i.e. responses of positions 6 through 10 would have been correct with this criterion. The dominant force criterion was easier for the subjects than the first two criteria, and therefore was expected to exhibit the highest success rate of the three criterion analyzed.

Primarily, these psychophysical experiments were intended to obtain some basic information on the ability of the two sensory displays to present multiple force positions. However, these tasks were also performed with the intention of providing some insights into performance results for the four sided peg-in-hole experiments when the auditory and vibrotactile displays were used. Since these psychophysical tests focused only on the two sensory substitution displays, perhaps the most valuable correlations were drawn from the psychophysical results when analyzing performance with the sensory substitution displays and an obstructed view. During the obstructed view conditions, the subjects were totally dependent on sensory substitution to perform the task. Therefore differences in obstructed view performance for the four sided peg-in-hole experiments, both with and without time delay, could be related to the psychophysical experimental results. The relationships between the results of these psychophysical tests and the results of the teleoperation experiments will be discussed in chapter 10 of this thesis.

Each of the criteria tested each display's ability to present different amounts of information about the position of the force, and consequently the peg, in the hole. The first criterion, exact force position, was the most stringent test and required high accuracy for a correct response. This criterion was expected to be important if the task conditions left the operator in need of information regarding the task. Such conditions would occur if the task was relatively difficult due to for example, and obstructed view and a transmission time delay.

The dominant force criterion, criterion #3, was more important for predicting performance for peg-in-hole tasks under more desirable task conditions, for example, performance without a time delay. Recognizing the dominant force when performing the peg-in-hole tasks gave the operator a general idea of where the peg was with respect to the hole. Therefore simply a gross estimate of where the force was on the hole was useful for many teleoperation tasks.

The results for criterion #1, recognizing the exact position of the force, are shown in figure 60. The subjects were correct 66.9 % of the time on average with the auditory display and 45.7 % of the time with the vibrotactile display. This represented a significant difference ($t(3)=5.47, p<0.012$) between the two displays. Thus when using the auditory display, the subjects were able to recognize the exact force position significantly better than when using the vibrotactile display.

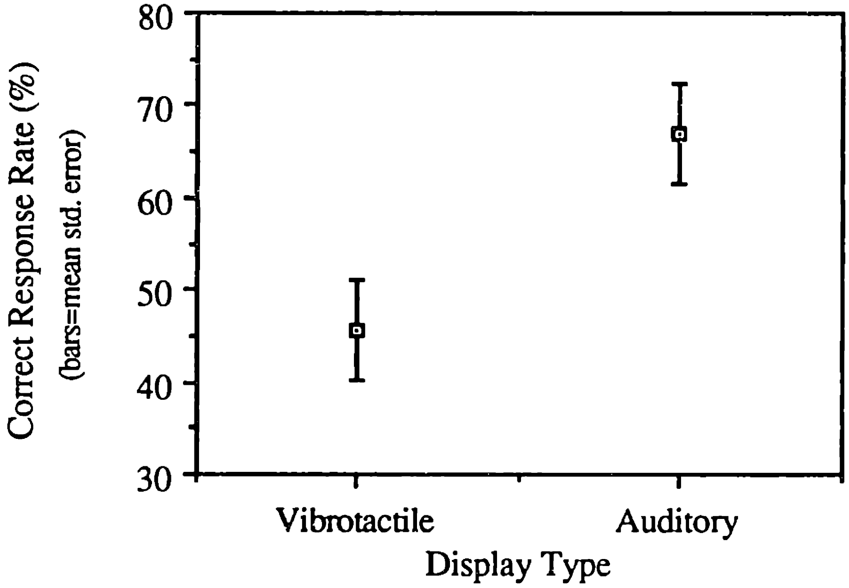

Figure 60 - Psychophysical Experiments - Results for Recognizing Exact Force Position (Criterion #1)

When comparing the subjects' abilities to recognize the correct quadrant of the hole in which the force was present (criterion #2), there was again a significant difference (t(3)=4.42,p<0.022) in favor of the auditory display. The auditory display had a 96.3 % success rate and the vibrotactile display had a 84.1 % success rate. The results are shown graphically in figure 61.

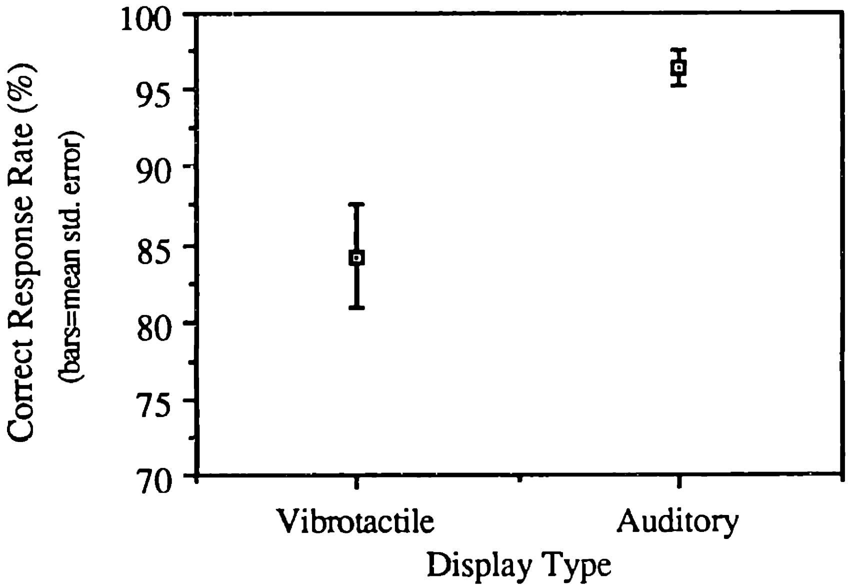

Figure 61 - Psychophysical Experiments - Results for Recognizing Correct Quadrant (Criterion #2)

The results for recognizing the dominant force component, criterion #3, are displayed in figure 62. A 98.8 % average success rate was calculated for the auditory display versus a 97.5% average success rate for the vibrotactile display. There was no significance difference between the two sensory substitution displays for this criterion.

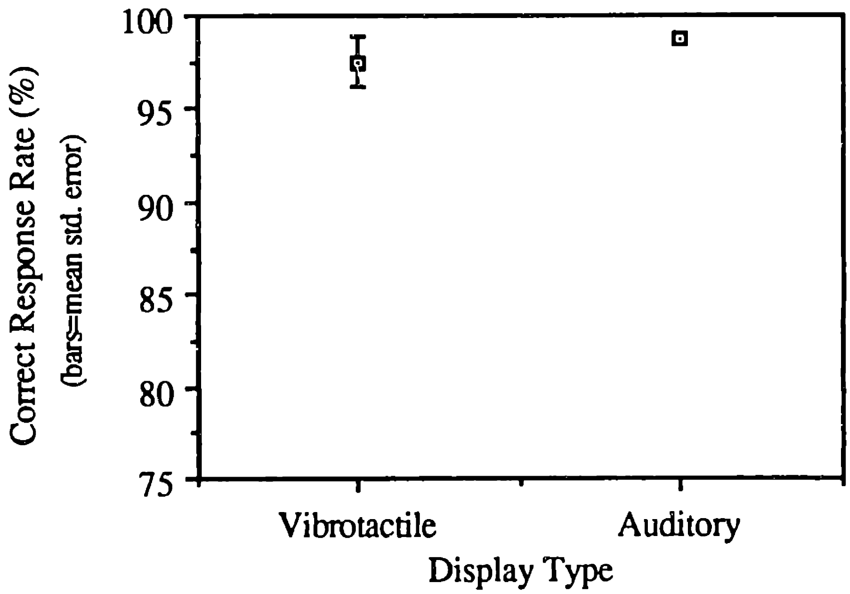

Figure 62 - Psychophysical Experiments - Results for Recognizing the Dominant Force Component

The auditory display was clearly superior to the vibrotactile display in determining the more precise location of the forces, i.e. the exact force position and the correct force quadrant. Whereas for determining a general idea of where the force was acting, i.e. the dominant force component, the vibrotactile and auditory displays performed equally as well.

6.2.2 - Results for Four Sided Peg-In-Hole Experiments with a Clear View

The actual peg-in-hole experiments with the four sided hole were conducted after the psychophysical experiments described above were completed. The task would start with the test subject moving the E2 slave arm away from a microswitch which would start a clock, and ended when the peg was inserted into the hole and made contact with another microswitch which would stop the clock and cause a contact light to light up indicating to the subject that the task was completed. Two microswitches could start the clock, one on the left side of task board, and one on the right side of task board. The subjects would alternate starting the task with the two microswitches to give alternating right and left starting points. Each side of the hole was one inch deep, and had a single force sensing resistor placed on each side (see figure 58) to detect the corresponding forces when using the sensory substitution displays. A force sensing resistor was also placed on the tip of the peg in order to measure the force exerted by the peg on the task board.

Four trained test subjects performed the tasks. They were trained by performing the tasks first informally to attain some familiarity, and then practice trials were conducted until the learning curves flattened and performance was stable. On average training for each task took approximately one to two hours. A counterbalanced experimental design was used to balance the effects of learning and fatigue during the experimental trials. Each subject performed ten trials for each experimental condition.

The strategy adopted by the subjects for these experimental conditions was to rely heavily on visual feedback. Since the visual feedback was clear and of high quality, they moved the peg directly to the hole by concentrating on the visual feedback.

The results for the experiments with a clear view are shown in table 13 and figure 63. Four feedback conditions were tested: 1) using the visual feedback through the television monitor alone without any force information , 2) combining visual feedback with traditional force feedback, 3) combining visual feedback with vibrotactile sensory substitution of force feedback, and 4) combining visual feedback with auditory sensory substitution of force feedback.

Feedback Condition	Mean Task Time (sec.)
No Force Feedback	2.39
Traditional Force Feedback	2.72
Vibrotactile Display of Sensory Substitution for Force Feedback	2.51
Auditory Display of Sensory Substitution for Force Feedback	2.80

Table 13 - Results for the Four Sided Peg-In-Hole Experiments with a Clear View

The results shown in figure 63 for the four sided hole differed with those found with the two sided hole (see figure 55). With the four sided hole it appeared as though force information could actually impede performance. Using the visual display alone without any force information provided significantly lower mean task times than combining visual feedback with traditional force feedback ($t(39)=2.62, p<0.012$) or with the auditory sensory substitution display ($t(39)=2.67, p<0.011$).

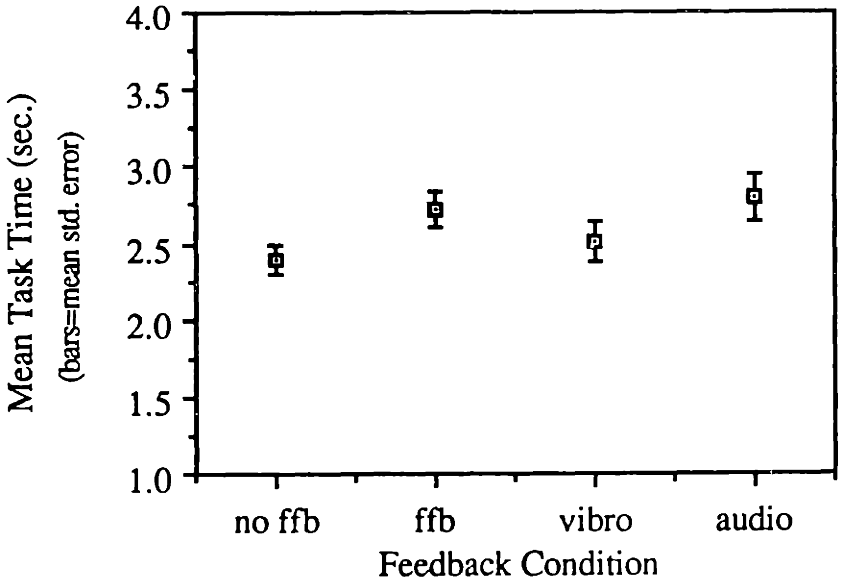

Figure 63 - Results for the Four Sided Peg-In-Hole Experiments with a Clear View

These results were quite surprising. To further understand these results, the reader is referred to the analysis presented in chapter 10 of this thesis.

6.2.3 - Results for the Four Sided Peg-In-Hole Experiments with an Obstructed View

With the obstructed view, the task was impossible to perform when relying only on visual feedback. Therefore only three experimental conditions could be tested: 1) traditional force feedback, 2) vibrotactile sensory substitution of force feedback, and 3) auditory sensory substitution of force feedback. The test subjects were totally reliant on force information to perform the task, visual feedback was of no significance in task performance.

The strategy that the test subjects used for obstructed view performance was different than that for performance with a clear view. They could no longer rely on moving the peg directly to the hole. Instead, they scanned the task board surface using up and down or side to side motions by applying forces with the manipulator. This was done until a major change in the applied force was detected. This change indicated to the test subjects that the hole had been located. The experimental results are shown in table 14 and figure 64.

Feedback Condition	Mean Task Time (sec.)
Traditional Force Feedback	6.34
Vibrotactile Display of Sensory Substitution for Force Feedback	15.7
Auditory Display of Sensory Substitution for Force Feedback	14.1

Table 14 - Results for the Four Sided Peg-In-Hole Experiments with an Obstructed View

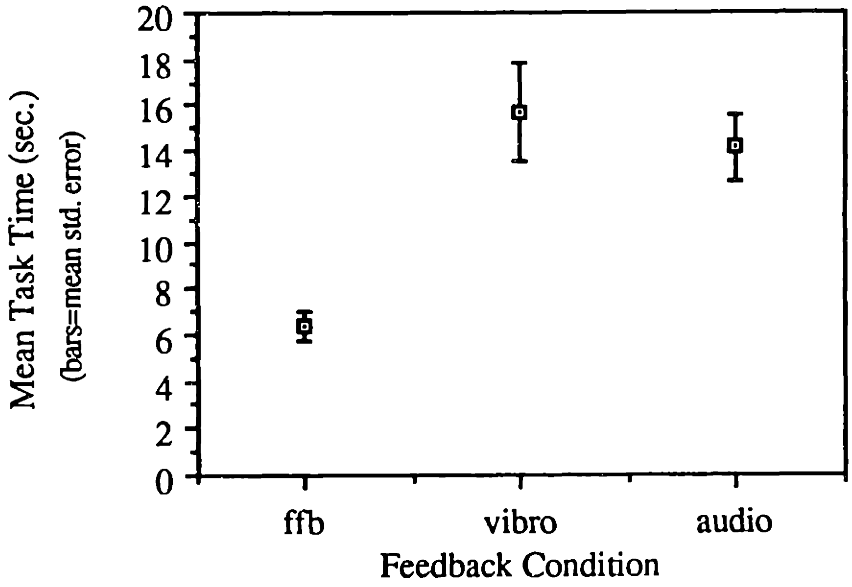

Figure 64 - Results for the Four Sided Peg-In-Hole Experiments with an Obstructed View

A series of paired t-tests showed similar results for the four sided peg-in-hole task with an obstructed view as those observed for the two sided hole task with an obstructed view. Mean task times with traditional force feedback were significantly lower than both the vibrotactile display (t(39)=4.05,p<0.001) and the auditory display (t(39)=5.0,p<0.001). The advantage given to traditional force feedback can probably be attributed to the fact that force feedback not only provided a cue to the operator concerning force information, but also forced the subjects' hands to proper positions so that insertion was quicker than with sensory substitution which only provided force cues. Therefore this was a case in which the forces on the subjects' hands helped performance unlike the results found for the clear view scenario shown in figure 63.

The most significant result of the obstructed view experiments, was that the task was performed successfully by using either the vibrotactile or auditory display without any useful visual feedback or traditional force feedback. Further analysis of these results is provided in chapters 9 and 10.

6.3 Training and Learning Effects

This section discusses a sample of the training and learning data that were recorded when conducting the four sided peg-in-hole experiments. It provides examples of how well the test subjects were able to adapt to performing the tasks, and to using the sensory substitution displays.

In general, throughout all of the experiments, training was efficient. After a few practice trials, subjects were able to perform the tasks successfully and their learning curves began to flatten. One contributing factor to the efficiency of the training, was that the same test subjects performed all of the experiments. Therefore, they had previous experience with the manipulator, the displays, and the procedures when they tried the more difficult manipulation tasks. The remainder of this section provides some example learning curves for one of the test subjects. The data are intended to give a few examples of how the subjects were able to learn the experiments quickly.

6.3.1 Learning Curves for the Peg-In-Hole Experiments with a Clear View

This section presents and discusses the learning curves for the test subject, when he performed the peg-in-hole manipulation task with the four sided hole and a clear (unobstructed) view. Figure 65 displays these learning curves.

The data in Figure 65 were taken from a training session that was held prior to the sessions in which experimental data was recorded. The same four feedback conditions that were tested during the actual experimental trials, were practiced during the training sessions. These conditions and the order in which the subject was trained with them were: 1) vibrotactile sensory substitution for force feedback plus visual feedback (denoted on the graph as "vibro"), 2) visual feedback alone ("no ffb"), 3) auditory sensory substitution for force feedback plus visual feedback ("audio"), and 4) traditional force feedback plus visual feedback ("ffb").

Curve fits for each of the conditions were calculated through logarithmic relationships. The slopes of the curves are related to the values of the exponents in the equations listed in figure 65. Therefore, the exponents provide estimates of the relative rates of learning between using the different feedback conditions. Higher absolute values of the exponent, indicate larger rates of learning.

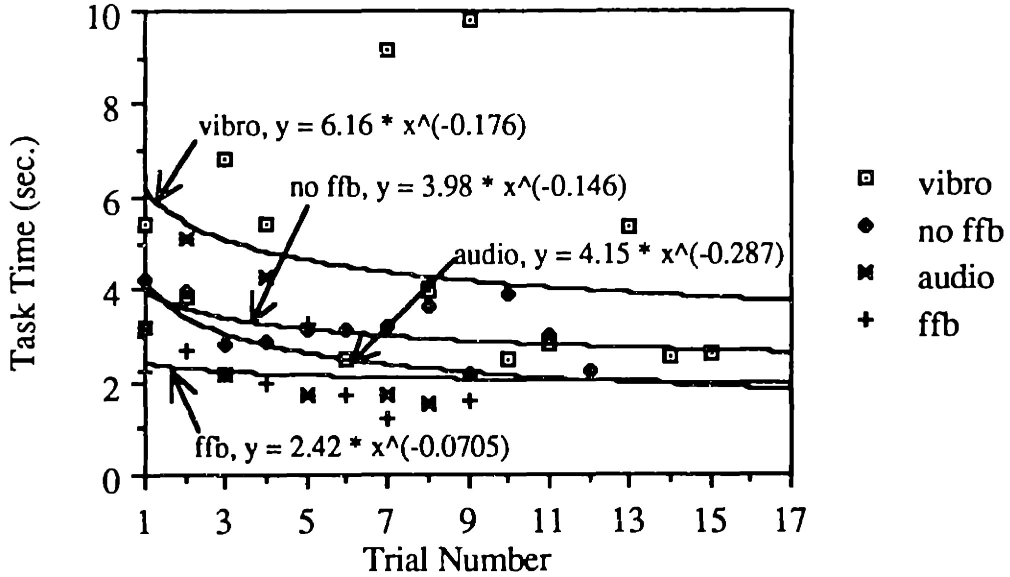

Figure 65 - Learning Curves for Peg-In-Hole Task with the Four Sided Hole and a Clear View

Figure 65 shows that some learning took place at all feedback conditions. It also shows that the data appear to have leveled off at asymptotic values after a certain number of trials had been completed.

The relative rate of learning appears to have been greatest with the sensory substitution displays, and least with traditional force feedback. Since the same task was performed with each condition, the displays on which the test subject was first trained would not only include learning effects from interpreting the displays, but also learning effects due to learning about the task itself. The vibrotactile display was the first condition which the test subject was trained. This probably contributed to its high learning rate, because its initial training task were the highest as well. Conversely, traditional force feedback was the last in line during training, which probably contributed to its having the lowest rate.

The main points are that learning took place during the training session, the learning effects seemed to asymptotically level off with time, and learning occurred at a fairly rapid pace. Therefore, the training session and the charting of the subject's learning was a useful exercise that contributed to making the experimental results more reliable.

6.3.2 Learning Curves for the Peg-In-Hole Experiments with an Obstructed View

Learning curves for the four sided peg-in-hole tasks with an obstructed view are displayed in figure 66, which shows that learning did take place, and that the task times approached an asymptotic value.

The obstructed view experiments were conducted after the clear view experiments were completed. Unlike the clear view experiments, training for the obstructed view experiments were conducted in the same session as the experimental trials. This was done because the subjects were already familiar with the task, from the training and experimental sessions conducted for the clear view experiments. Therefore, training for the obstructed view experiments was expedited somewhat. The subjects began with training and warm-up trials. After the learning effects were calculated to have reasonably subsided, which was indicated by a flattening learning curve, experimental trials were conducted. Figure 66 displays both the warm-up, or training, trials in addition to the actual experimental data. The experimental data are represented in the asymptotic regions shown on the graph.

The data in figure 66 were taken from the same subject as the data presented in figure 65. The three conditions tested and the order of presentation to the subject were: 1) vibrotactile sensory substitution for force feedback (denoted on the graph as "vibro"), 2) auditory sensory substitution for force feedback ("audio"), and 3) traditional force feedback ("ffb").

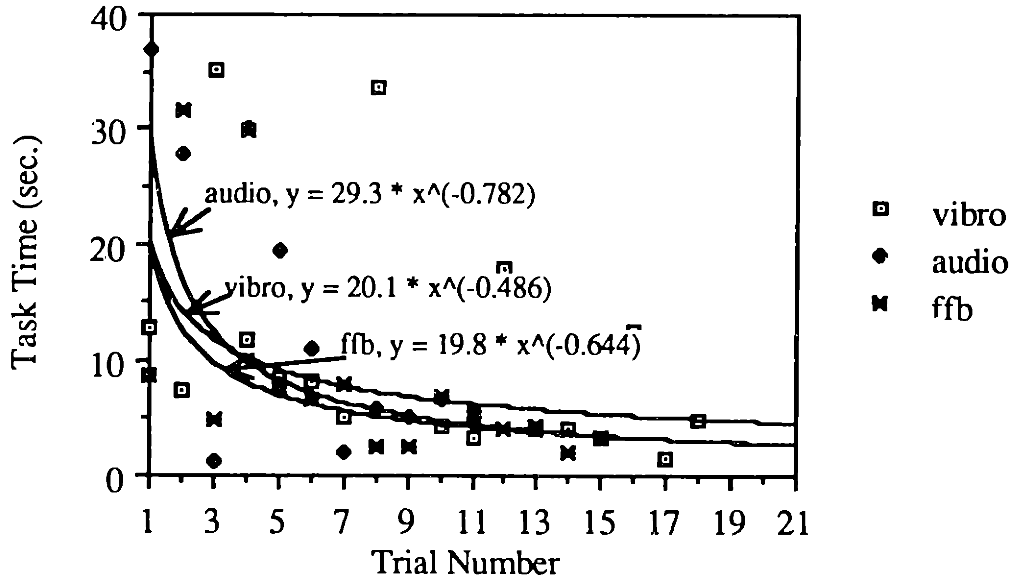

Figure 66 - Learning Curves for the Peg-In-Hole Task with the Four Sided Hole and an Obstructed View

The largest learning rate appears to have occurred with the auditory display, followed by traditional force feedback and the vibrotactile display. These results are different from those observed for the experiments with a clear view, in which the ordering of the presentation of the conditions appeared to have influenced the learning rates. However, the absolute values of the exponents in the curve fits were higher for the obstructed view experiments than with the clear view experiments. The initial task times, before learning had subsided, were also higher with the obstructed view than with the clear view. Therefore, both the rate of learning and the amount of learning was greater with the obstructed view than with the clear view. These effects were probably due to the subject needing to learn to rely totally on force information to perform the task with an obstructed view. This was not the case with the clear view experiments, which allowed the subjects to rely on visual feedback.

Perhaps the most important finding from examining the learning data with an obstructed view, is that the test subjects could quickly learn to interpret the sensory substitution displays and perform the task successfully without useful visual information.

7. TIME DELAYED TELEOPERATION

To accommodate the investigation of using sensory substitution with a time delay, the peg-in-hole tasks described in chapter 6 were repeated with a three second time delay. When operating with a time delay, traditional bilateral force feedback to the operator's hand and arm muscles can lead to instabilities. For example, if an operator moves a controller with his hand or arm to input a command to the system in the presence of a three second round trip time delay, it will take approximately 1.5 seconds for the slave arm to react to the feedforward signal. Once the slave arm moves, if it hits an object in the remote environment or encounters some disturbance, the slave will send that signal back to the master arm. This signal will be received by the master approximately 1.5 seconds later through the feedback loop. If bilateral force feedback is present, the master arm will react to the forces or disturbances present in the remote environment and will reflect them to the operator's hand and arm. This, however, is not only feedback, but has also become another input, an unwanted input which will reach the slave arm after the feedforward time delay. This process will repeat itself, and the disturbances that are reflected back to the operator and directly input back into the system will begin to multiply, thus leading to instability. This is why traditional force feedback is unacceptable in the presence of even small time delays.

Ferrell [1964,1965] found that tasks could be accomplished in the presence of a time delay without force feedback by adopting a simple strategy of performing the task with a series of discrete, open loop movements. He also found that operator performance with a time delay could be predicted from performance measures taken without a time delay. When studying time delay performance with force feedback Ferrell [1966] found that force feedback's primary advantage, the tight closed loop control over force that it gives the operator, is lost with delay and presented the danger of unstable operator induced movements. Ferrell [1966] and Bliss and Hill [1971] suggested that tactile displays that provide force feedback could be particularly useful in the presence of a time delay since it would not interfere with manipulation as bilateral force feedback would.

Reger [1987] used the JPL Force Visual Display (FVD) with a master-slave system and a one second time delay. He found that the additional presence of visually displayed force feedback information significantly improved an operator's ability to apply and manage low, stable forces under real time and delay conditions. However subjects took significantly longer to make initial contact with the task surface. This significant increase in time was most probably due to an increase in operator workload due to the divided attention of the visual modality by being required to simultaneously monitor the remote task scene and the force display visually.

Since the vibrotactile and auditory displays do not force the operator's hand or arm when presenting force information, they do not create unwanted operator inputs into the system and therefore should not cause the system to go unstable. In addition, they do not directly add any additional burden on the visual modality. Therefore the use of sensory substitution of force feedback with auditory and vibrotactile displays in the presence of time delay may be particularly advantageous. In order to facilitate the time delay experiments, the E2 manipulator was interfaced with a Macintosh II PC as was described in chapter three. The experiments described in the following sections measured the effects of sensory substitution of force feedback on teleoperator performance with a time delay, identified the improvements in task performance due to sensory substitution, and determined that the auditory and vibrotactile displays did not produce any instabilities.

7.1 Time Delay Experiments for Peg-In-Hole Tasks with a Two Sided Hole

The two sided peg-in-hole tasks discussed in section 6.1 were performed with a three second time delay. The tasks were started differently then when no time delay existed, because positioning the E2 on the starting microswitch with a time delay became too difficult and time consuming. The test subjects would place the E2 in a starting area, then they would watch a start indication light. When the light went out, the test subjects began the task by moving the E2. The clock was electronically coupled to the light, and would start recording the task time when the light went out. The task ended when the peg was inserted into the hole and made contact with the microswitch in the back of the hole which would stop the clock and cause a contact light to light up, indicating to the operator that the task was completed. The subjects would alternate starting the task between the right and left sides of the task board. The task board and the arrangement of the force sensing resistors were exactly those used for the peg-in-hole tasks discussed in chapter 6.

The same four trained test subjects that were tested for all the other experiments described in this thesis performed these time delay tasks as well. They were trained by performing the tasks first informally to attain some familiarity, and then practice trials were conducted until the learning curves flattened and performance was stable. A counterbalanced experimental design was used to balance the effects of learning and fatigue during the experimental trials. Each subject performed ten trials for each experimental condition.

7.1.1 Results for the Time Delay Experiments with the Two Sided Peg-In-Hole Tasks and a Clear View

Both the clear and obstructed visual views were tested. Since a time delay was present, traditional force feedback would lead to instability and could not be tested. Therefore traditional force feedback was eliminated as a task condition from the experimental design, and only three feedback conditions were possible with a clear view: 1) using the visual feedback through the television monitor alone without any force information, 2) combining visual feedback with sensory substitution for force feedback through the vibrotactile display, and 3) combining visual feedback with sensory substitution for force feedback through the auditory display. The results for two sided peg-in-hole time delay experiments with a clear view are listed in table 15 and shown in figure 67.

Feedback Condition	Mean Task Time (sec.)
No Force Feedback	15.1
Vibrotactile Display of Sensory Substitution for Force Feedback	11.2
Auditory Display of Sensory Substitution for Force Feedback	10.1

Table 15 - Results for the Two Sided Peg-In-Hole Time Delay Experiments with a Clear View

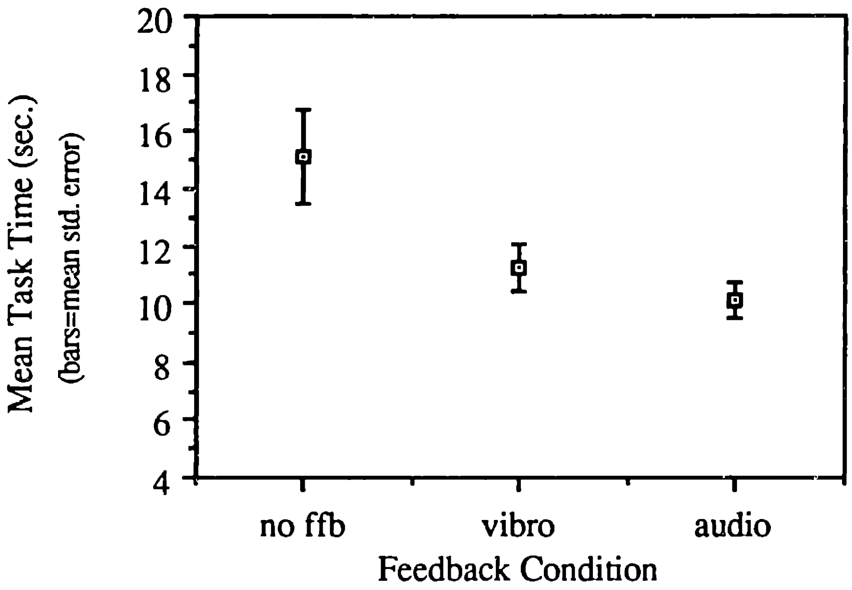

Figure 67 - Results for Two Sided Peg-In-Hole Time Delay Experiments with a Clear View.

The experimental results showed that unlike performance without a time delay, performance with a time delay was affected by using sensory substitution in combination with visual feedback. The vibrotactile display ($t(39)=2.25, p<0.03$) and the auditory display ($t(39)=3.37, p<0.002$) both had significantly lower mean task times than using only visual feedback without any force information. There was no significant performance difference between using the auditory and vibrotactile displays.

Using sensory substitution provided a significant improvement. Thus when operating with a time delay, visual feedback by itself did not provide sufficient information in order to maximize subject performance. These results were much different than the results obtained when the task was performed without a time delay, and vision alone was able to maximize performance (see section 6.1.1). The reasons behind these performance differences due to the time delay are analyzed in chapter 9.

7.1.2 Results for the Time Delay Experiments with the Two Sided Peg-In-Hole Tasks and an Obstructed View

When using a fully obstructed view, only two feedback conditions were possible since performing the task with visual feedback by itself was impossible, and performing the task with traditional force feedback led to instabilities. The feedback conditions tested were: 1) vibrotactile sensory substitution of force feedback, and 2) auditory sensory substitution of force feedback.

Performance between using the vibrotactile and auditory displays was not significantly different. The major result from these tests was the demonstration that it was possible to perform the task with a time delay and without any useful visual information. This task would be impossible under conventional means since neither visual feedback or traditional force feedback could help the operator perform the task. Thus sensory substitution made it possible to successfully complete a task that would normally be impossible to perform. Table 16 and figure 68 show the results of the two sided peg-in-hole time delay experiments with an obstructed view.

Feedback Condition	Mean Task Time (sec.)
Vibrotactile Display of Sensory Substitution for Force Feedback	21.2
Auditory Display of Sensory Substitution for Force Feedback	20.3

Table 16 - Results from the Two Side Peg-In-Hole Time Delay Experiments with and Obstructed View

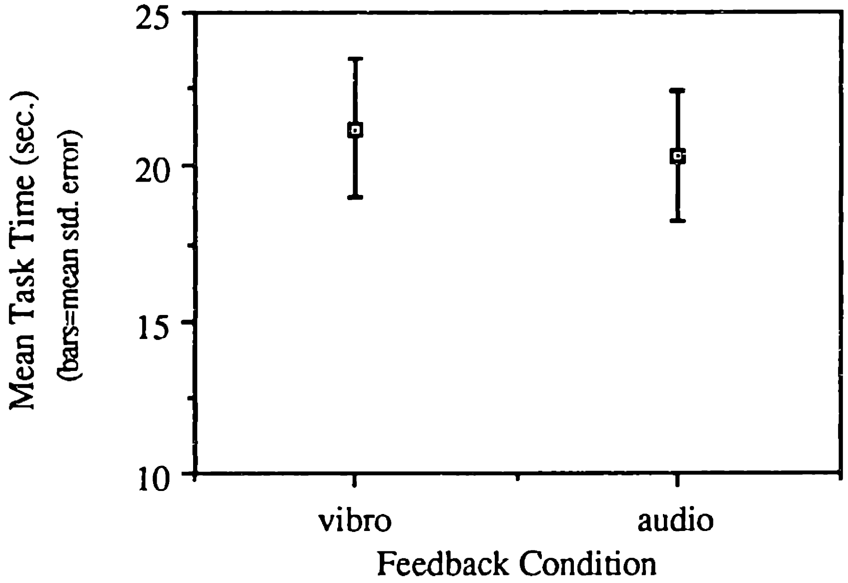

Figure 68 - Results from the Two Sided Peg-In-Hole Time Delay Experiments with an Obstructed View

7.2 Time Delay Experiments for Peg-In-Hole Tasks with a Four Sided Hole

The peg-in-hole tasks described in section 6.2 were conducted with a three second time delay. The same task board and force sensing resistor arrangement detailed in section 6.2 was used. The only difference was that instead of starting the task by braking contact with a microswitch which started the clock, the test subjects would place the E2 in a starting area and would watch a start indication light. When the light went out, the test subjects began the task by moving the E2. The task ended when the peg was inserted into the hole and made contact with the microswitch in the back of the hole which would stop the clock and cause the contact light to light up, indicating to the subject that the task was completed.

7.2.1 Results for the Time Delay Experiments with the Four Sided Peg-In-Hole Tasks and a Clear View

The results for the four sided peg-in-hole time delay experiments with a clear view are shown in table 17 and figure 69. Three feedback conditions were tested: 1) using the visual feedback through the television monitor alone without any force information, 2) combining visual feedback with vibrotactile sensory substitution of force feedback, and 3) combining visual feedback with auditory sensory substitution of force feedback.

To perform these time delay tasks, the subjects primarily adopted a move and wait strategy to successfully insert the peg into the hole.

Feedback Condition	Mean Task Time (sec.)
No Force Feedback	30.0
Vibrotactile Display of Sensory Substitution for Force Feedback	22.9
Auditory Display of Sensory Substitution for Force Feedback	22.1

Table 17 - Results for the Four Sided Peg-In-Hole Time Delay Experiments with a Clear View

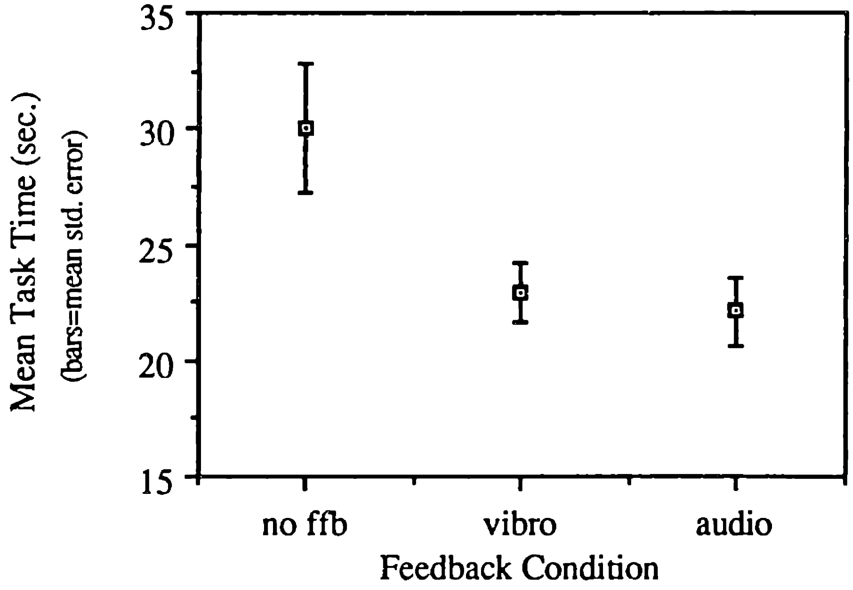

Figure 69 - Results from the Four Sided Peg-In-Hole Time Delay Experiments with a Clear View

The results shown in table 17 and figure 69 exhibit the same behavior as those obtained for the two sided hole case (see figure 65), since both the vibrotactile display (t(39)=2.32,p<0.025) and the auditory display (t(39)=2.53,p<0.016) had significantly lower mean task times than using only visual feedback. These results will be analyzed in chapter 9.

7.2.2 Results for the Time Delay Experiments with the Four Sided Peg-In-Hole Tasks and an Obstructed View

With the obstructed view, the task was impossible to perform when relying only on visual feedback. Therefore only two experimental conditions could be tested: 1) vibrotactile sensory substitution of force feedback, and 2) auditory sensory substitution of force feedback. The test subjects were totally reliant on sensory substitution of force information to perform the task, visual feedback was of no significance in task performance.

The subjects adopted new strategies to perform these tasks. These new strategies mainly consisted of combinations of the scanning strategy, which was used during obstructed view experiments, and the move and wait strategy, which was utilized during the time delay tasks. The strategy predominantly used to perform the obstructed view time delay tasks was a "scan and wait" strategy. The subjects would scan the task board and then wait to see if the hole had been encountered. If it had, they would interpret the cues to determine the position of the peg in relation to the hole, and then attempt to insert the peg into the hole. If no contact with the hole was detected, they would repeat the scan and wait strategy.

The experimental results are shown in table 18 and figure 70.

Feedback Condition	Mean Task Time (sec.)
Vibrotactile Display of Sensory Substitution for Force Feedback	70.5
Auditory Display of Sensory Substitution for Force Feedback	52.7

Table 18 - Results for the Four Sided Peg-In-Hole Time Delay Experiments with an Obstructed View

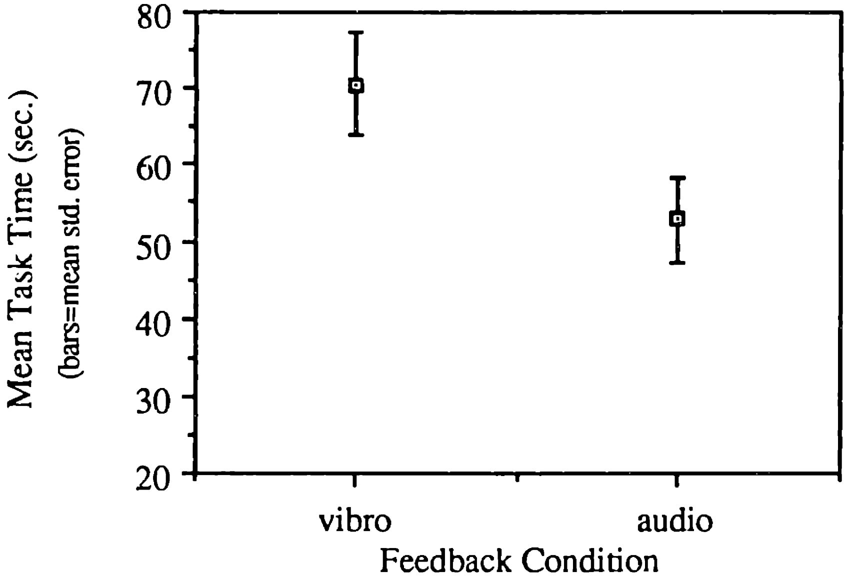

Figure 70 - Results for the Four Sided Peg-In-Hole Time Delay Experiments with an Obstructed View

For performing the obstructed view scenario with the four sided hole and a time delay, the results were different from those obtained with the two sided hole obstructed view experiments with a time delay. There was a significant difference in mean task time between using the vibrotactile or auditory displays (t(39)=2.14,p<0.04), with the auditory display producing significantly better performance.

The most significant result was that this task, which could not be completed with visual feedback alone and could not be done with traditional force feedback due to instabilities, was completed successfully by using either of the sensory substitution as the sole source of feedback. These results are analyzed, with respect to the results of the psychophysical experiments on interpreting force direction, in chapter 10.

7.3 Learning Curves for Time Delay Experiments

This section discusses the learning effects that occurred during of the time delay experiments with the four sided peg-in-hole task. It provides examples of how a test subject was able to adapt to performing the tasks, and to using the sensory substitution displays in the presence of a time delay.

As was the case with the experiments conducted without a time delay, training was efficient. After a few practice trials, subjects were able to perform the tasks successfully and their learning curves began to flatten. A contributing factor to the quickness of the learning, was that the test subject had already been tested on using the displays while performing the task without a time delay.

7.3.1 Learning Curves for the Time Delay Experiments with a Clear View

Learning curves for performing the four sided peg-in-hole task with a three second time delay and a clear view are shown in figure 71. The data shown were collected from a single test subject.

The feedback conditions tested for the time delayed experiments with a clear view and the order in which they were presented to this particular subject were: 1) vibrotactile sensory substitution for force feedback plus visual feedback (denoted on the graph as "vibro"), 2) visual feedback alone ("no ffb"), and 3) auditory sensory substitution for force feedback plus visual feedback ("audio").

Curve fits for each of the conditions were calculated through logarithmic relationships. The slopes of the curves are related to the values of the exponents of the equations listed in figure 71. Therefore, the exponents provide estimates of the relative rates of learning between using the different feedback conditions. Higher absolute values of the exponent, indicate larger rates of learning.

Figure 71 displays that the rate of learning was greatest with the vibrotactile display. This corresponds to the fact that the vibrotactile display was the first condition under which this subject learned to perform the task with a time. Therefore, some of this large rate of learning was probably due to the subject getting adjusted to the time delay.

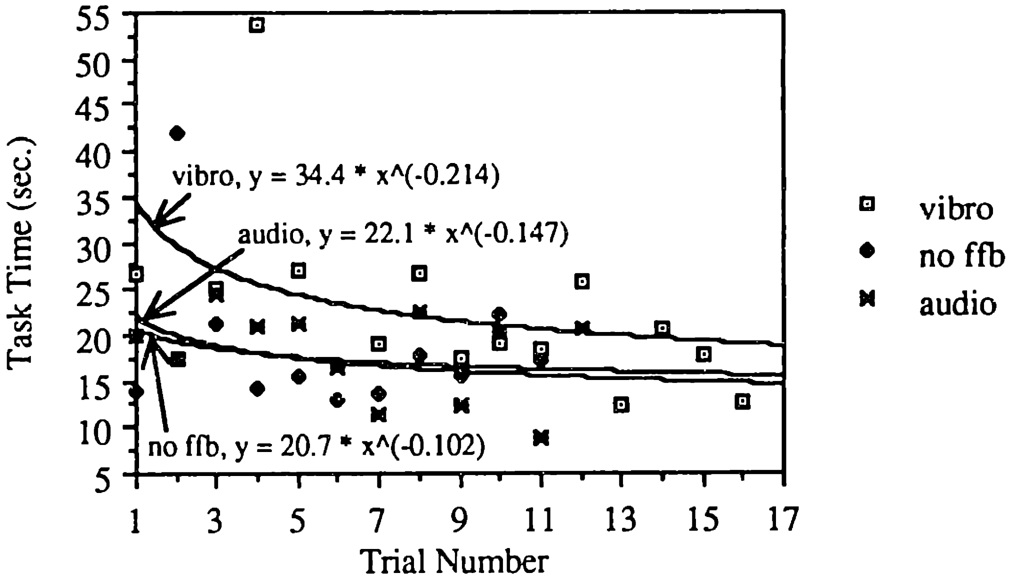

Figure 71 - Learning Curves for the Time Delayed Peg-In-Hole Task with the Four Sided Hole and a Clear View

As can be seen in figure 71, learning did take place and approached an asymptotic value. Therefore the test subjects did require some learning to get adjusted to performing the task with a time delay. Allowing these learning effects to subside before experimental data were taken, helped to make the experimental data more reflective of actual performance differences between the experimental conditions.

7.3.2 Learning Curves for the Time Delay Experiments with an Obstructed View

The most difficult task scenario was performing the four sided peg-in-hole task with a three second time delay and an obstructed view. This was also the very last set of experiments that the test subjects performed. Therefore, they had already been trained and had experience with using the manipulator, performing the peg-in-hole task, interpreting the displays, and performing the task in the presence of a time delay. Figure 72 displays the learning curves for the time delayed obstructed view experiments for the same test subject whose data was shown in figure 71.

The feedback conditions tested for the time delayed experiments with an obstructed view and the order in which they were presented to this particular subject were: 1) vibrotactile sensory substitution for force feedback (denoted on the graph as "vibro"), and 2) auditory sensory substitution for force feedback ("audio").

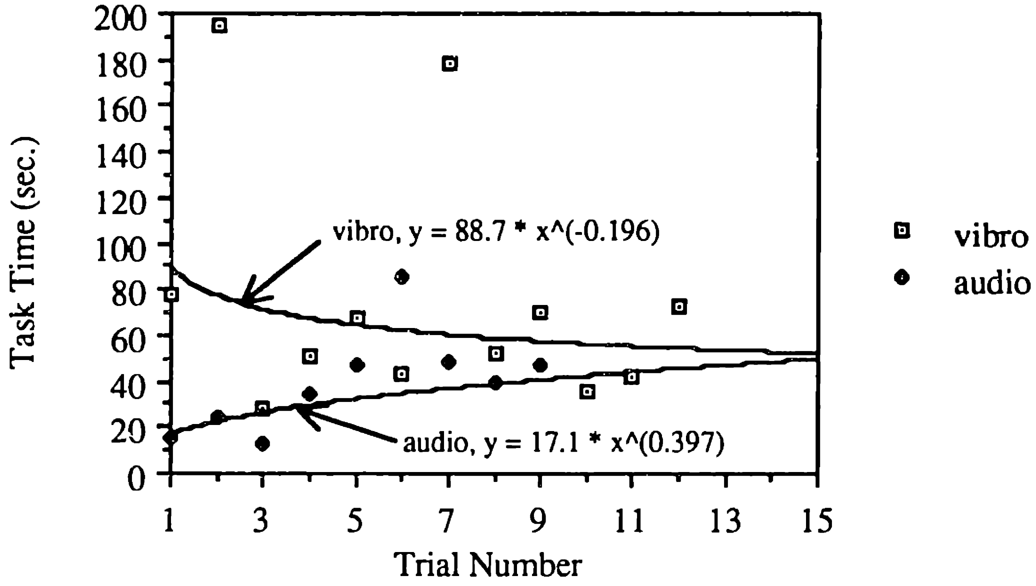

Figure 72 - Learning Curves for the Time Delayed Peg-In-Hole Experiments with the Four Sided Hole and an Obstructed View

Figure 72 shows some unusual learning behavior. The auditory display actually showed that the task times increased over time. This suggests that the inverse of learning actually occurred over time, probably due to fatigue from performing this very difficult task. This was a case in which too much warm-up or training could actually be detrimental to acquiring good experimental results. For this reason, minimal warm-up was given to the test subjects before the experimental data were recorded.

The most interesting conclusion to be drawn from examining the learning data with a time delay and an obstructed view, is that the test subjects could efficiently learn to interpret the sensory substitution displays and perform the task successfully without useful visual information in the presence of a three second time delay.

8. SUMMARY OF EXPERIMENTAL RESULTS

This chapter summarizes and quickly reviews the results for each of the teleoperation experiments that were described in Chapters 5 through 7. It provides a bridge into Chapters 9 and 10, in which the experimental results are analyzed and explanations of the performance differences between the experimental conditions are proposed.

Each of the diagrams in this chapter is divided into four parts horizontally by feedback condition: 1) visual feedback alone, 2) traditional force feedback plus visual feedback, 3) sensory substitution of force feedback through the vibrotactile display plus visual feedback, and 4) sensory substitution of force feedback through the auditory display plus visual feedback. Icons are used to represent the different types of feedback: the eyeball represents visual feedback, the hand on the control stick represents traditional force feedback, the stimulated fingertip represents vibrotactile sensory substitution of force feedback, and the earphones represent auditory sensory substitution of force feedback.

The lines with the arrows signify a comparison of the performance between two of the feedback conditions. The direction of the arrows indicates the direction of a significant improvement in performance between the two conditions that are connected. If no arrow exists between two conditions, there was no significant performance difference between the conditions. For example, an arrow going from "visual feedback alone" to "traditional force feedback plus visual feedback" indicates a comparison between those two conditions. The direction of that arrow indicates that the combination of traditional force feedback plus visual feedback provided significantly better performance than using the visual display alone.

The lengths of the arrows do not reflect the magnitude of the differences between the conditions. However, the numbers that are listed with the arrows indicate the mean performance improvement between the two conditions. The units of the improvement are either mean number of taps or mean task time, depending on the task. For example, figure

73 summarizes the results for the presence of object contact force experiments in which the performance was measured by the number of taps made. Therefore the numbers above the arrows indicate the differences in mean number of taps between the two feedback conditions. However, if the experimental results were measured by task time, as they were during the sustained object contact force experiments (figure 75), then the numbers above the arrows indicate the difference in mean task time (in seconds) between the two feedback conditions.

8.1 Summary of Experimental Results for Object Contact Experiments

Basic force information was measured during the object contact experiments. These experiments were described in detail in Chapter 5, and focused on 1) detecting the presence of a contact force, 2) interpreting the magnitude of a contact force, and 3) tracking changes in a sustained contact force.

8.1.1 Summary of Results for the Presence of Object Contact Force Experiments

Figure 73 displays a summary of the results obtained for the experiments that investigated the ability of sensory substitution to display the presence of an object contact force. These experiments were conducted to measure the usefulness of sensory substitution in displaying the presence of a contact force. A detailed description of the experimental procedures and data was provided in section 5.1.

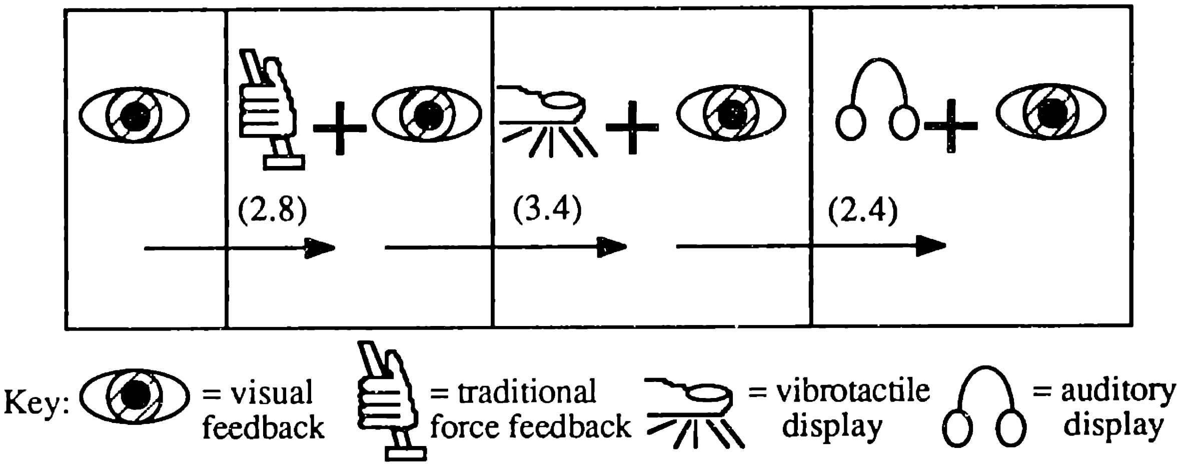

Figure 73 - Summary of Results for Presence of Object Contact Force Experiments (arrows indicate direction of significant performance improvement between two conditions; numbers indicate improvement in mean number of taps between two conditions)

When comparing visual feedback alone to either 1) traditional force feedback plus a visual display of the task, or 2) sensory substitution of force feedback with the auditory display plus a visual display of the task, or 3) sensory substitution of force feedback with the vibrotactile display plus a visual display of the task, performance was improved significantly when some type of force information was presented along with the visual feedback. These results, that favored the use of force information in addition to visual feedback, are analyzed in Chapter 9.

When substituting traditional force feedback with sensory substitution, sensory substitution through both the auditory and vibrotactile displays provided improved task performance. Further, when comparing the two sensory substitution displays to each other, the auditory display had significantly better performance than the vibrotactile display. Explanations for these performance differences between traditional force feedback and each of the sensory substitution displays are presented in Chapter 10.

8.1.2 Summary of Results for the Magnitude of Object Contact Force Experiments

Figure 74 summarizes the results for the magnitude of object contact force experiments. The objective of these experiments was to measure the ability of sensory substitution to present information on the magnitude of a contact force to a human operator. The method and the data for these experiments were discussed in detail in section 5.2.

These experiments were divided into tests of two force ranges: a high force range in which contact forces of 0 to 2 pounds would be acceptable and not cause unwanted displacement, and a low force range in which contact forces of 0 to 0.5 pounds would be acceptable. These two force ranges were tested to measure force magnitude perception capabilities for very light touch, and for relatively large applied forces.

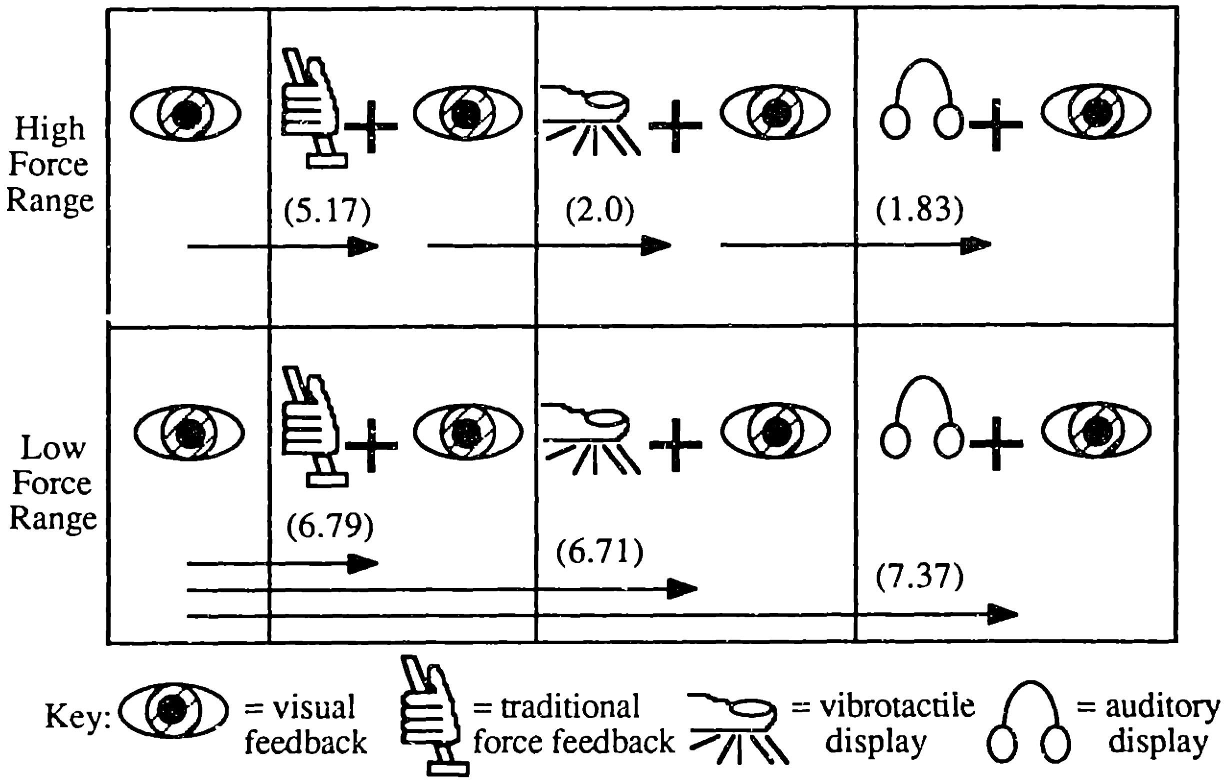

Figure 74 - Summary of Results for Magnitude of Object Contact Force Experiments (arrows indicate direction of significant performance improvement between two conditions; numbers indicate improvement in mean number of taps between two conditions)

For both the high and the low force ranges, adding traditional force feedback or sensory substitution of force feedback to visual feedback significantly improved performance. Further, significant performance improvements were also found at the high force range, when traditional force feedback was replaced with sensory substitution through either the auditory or vibrotactile displays. There was also a significant difference in performance between using the auditory and vibrotactile displays at the high force range, with the auditory display providing better performance. However, at the low force range, exchanging traditional force feedback with sensory substitution of force feedback made no significant difference in performance, and there was no significant performance difference when comparing the auditory display to the vibrotactile display. Chapter 10 analyzes these varying results, obtained when replacing traditional force feedback with sensory substitution at different force ranges.

8.1.3 Summary of Results for the Sustained Object Contact Force Experiments

To measure the usefulness of sensory substitution for presenting information to an operator who needs to track the changes in the magnitude of a sustained force, sustained object contact force experiments were conducted (for details see section 5.3). When tracking changes in a sustained contact force, adding traditional force feedback or sensory substitution of force feedback to visual feedback improved performance for both the high and low force ranges as is displayed in figure 75.

Exchanging traditional force feedback with sensory substitution of force feedback made no significant difference in performance at either of the force ranges tested. There was also no significant difference in performance when using either of the sensory substitution displays at both force ranges. Analysis of these results, which displayed no significant difference between using sensory substitution and traditional force feedback, will be provided in Chapter 10.

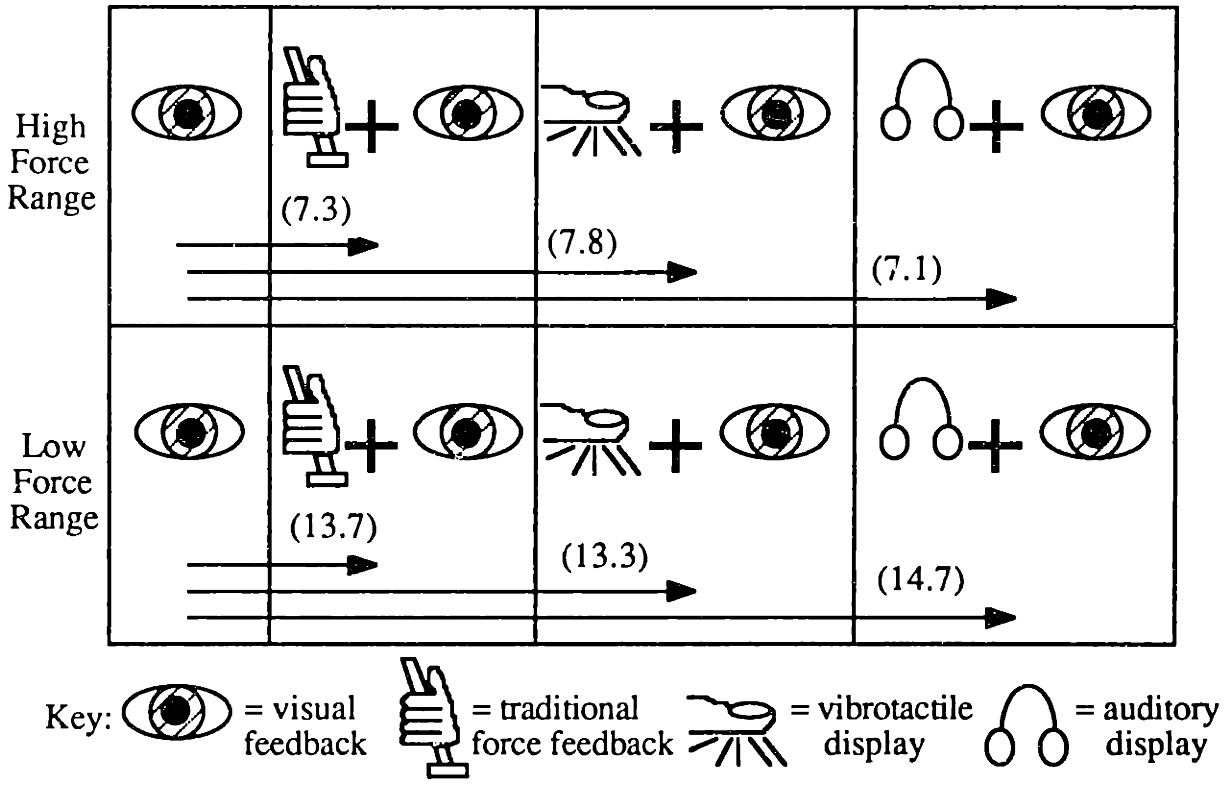

Figure 75 - Summary of Results for Sustained Object Contact Force Experiments (arrows indicate direction of significant performance improvement between two conditions; numbers indicate improvement in mean task time (seconds) between two conditions)

8.2 Summary of Results for Common Manipulation (Peg-In-Hole) Tasks

This section summarizes the experimental results that were found for the common manipulation, i.e. peg-in-hole, tasks. These experiments were described in detail in Chapter 6, and had three major objectives: 1) to examine the ability of sensory substitution to display force position information, 2) to examine the capabilities of sensory substitution during typical manipulation tasks of varying difficulty, and 3) to measure any changes in the usefulness of sensory substitution as visual conditions were degraded.

Peg-in-hole tasks were selected because they required the operator to determine the position of the peg with respect to the hole for successful manipulation. Thus when receiving force cues, the subjects needed to correctly interpret the direction and position of the force, applied by the peg with respect to the hole, in order to have force information aid with performing the task.

In order to examine typical manipulation tasks of varying difficulties, the experiments consisted of two types of peg-in-hole tasks: 1) an easier manipulation task which consisted of a peg-in-hole task with a two sided hole or slot, and 2) a more difficult peg-in-hole task with a four sided hole. In addition, these tests were conducted with obstructed and unobstructed views, to accommodate the testing of sensory substitution under clear and degraded visual conditions.

8.2.1 Summary of Results for the Simple Manipulation Task (2 Sided Peg-In-Hole Task)

When performing the peg-in-hole task with the two sided hole during the unobstructed visual condition, adding traditional force feedback or sensory substitution of force feedback to visual feedback had no effect on performance (see figure 76). The ineffectiveness of force information on performance during these tasks is analyzed in chapter 9.

However, when the view was obstructed, using traditional force feedback or sensory substitution of force feedback allowed the task to be performed. This was an important finding because the task was impossible if one were using visual feedback alone, but was possible when relying on sensory substitution.

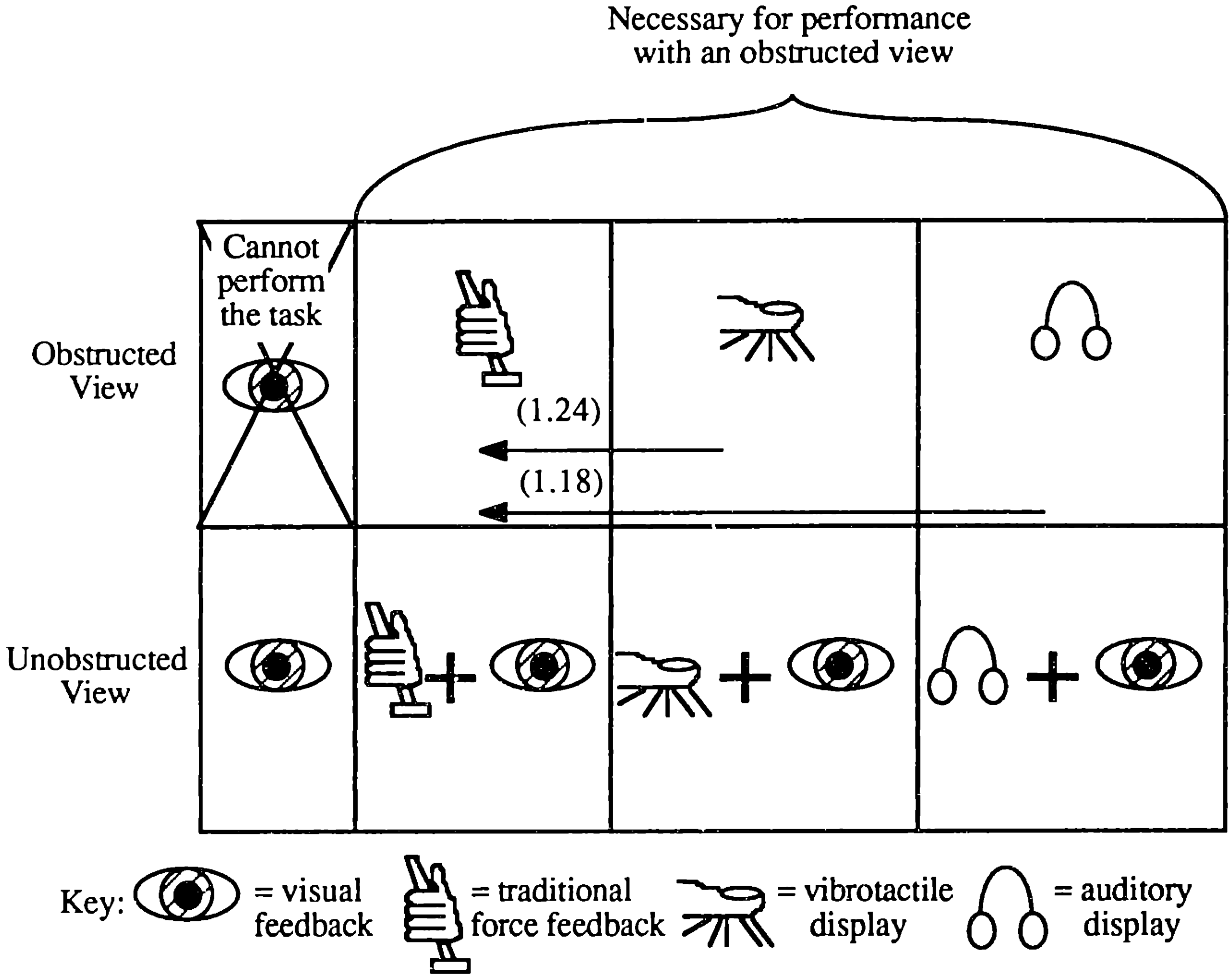

Figure 76 - Summary of Results for Peg-In-Hole Experiments with a Two Sided Hole (arrows indicate direction of significant performance improvement between two conditions; numbers indicate improvement in mean task time (seconds) between two conditions)

Exchanging traditional force feedback with sensory substitution of force feedback made no difference in performance with an unobstructed view, but led to a performance decrement with an obstructed view. These performance differences, recorded during the obstructed view experiments, between using traditional force feedback and sensory substitution are analyzed in Chapter 10.

8.2.2 Summary of Results for the More Complex Manipulation Task (4 Sided Peg-In-Hole Task)

The results for the more difficult peg-in-hole task, with a four sided hole, were similar to those results obtained with the two sided hole for scenarios with an obstructed view. However, the results were different than those found previously with an unobstructed view. When performing the peg-in-hole task with the four sided hole and an unobstructed view, adding traditional force feedback or sensory substitution of force feedback through the auditory display to visual feedback degraded performance as is displayed in figure 77. An analysis of these surprising results are presented in Chapters 9 and 10.

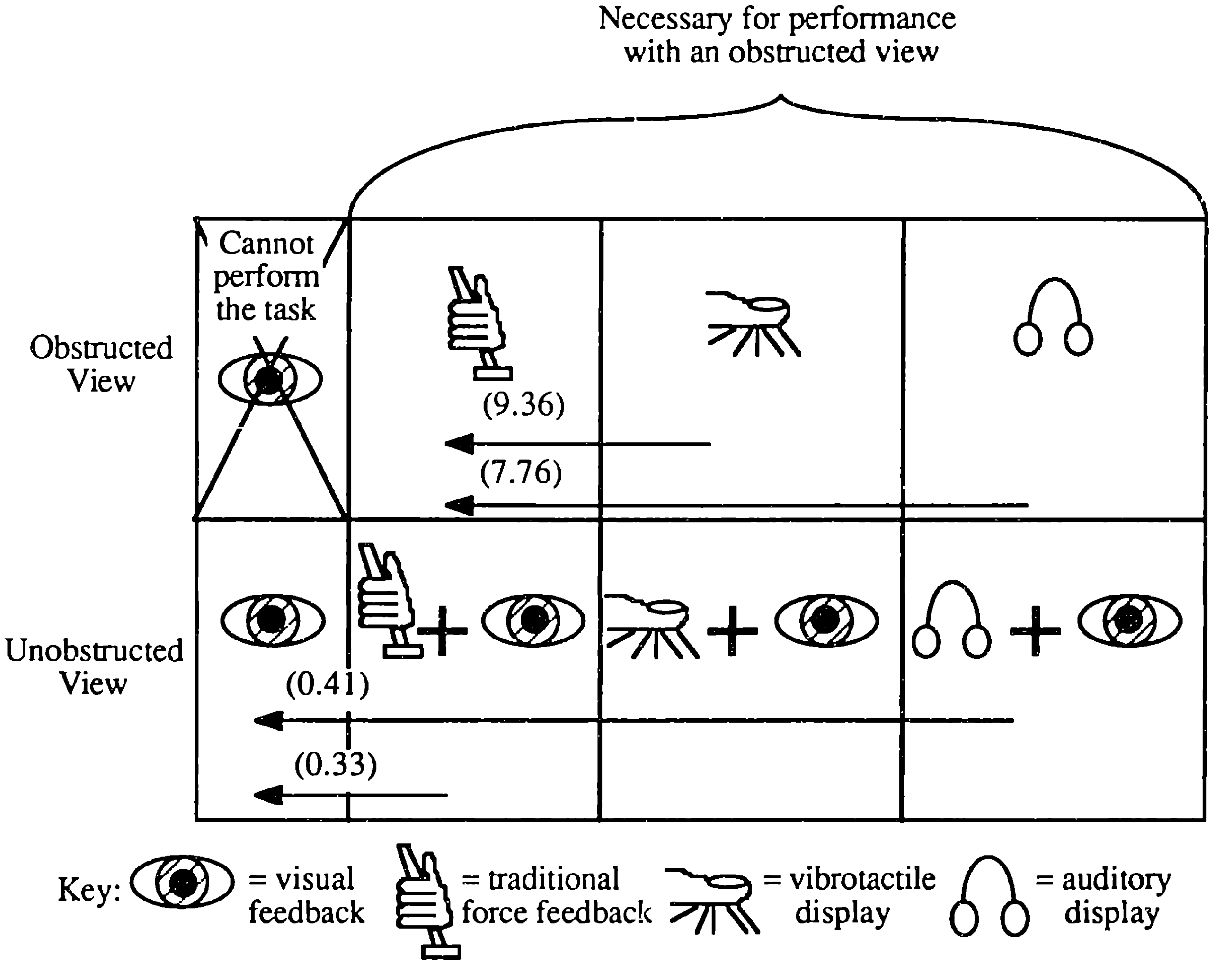

Figure 77 - Summary of Results for Peg-In-Hole Experiments with a Four Sided Hole (arrows indicate direction of significant performance improvement between two conditions; numbers indicate improvement in mean task time (seconds) between two conditions)

However, when the view was obstructed, using traditional force feedback or sensory substitution of force feedback enabled the task to be successfully completed without any useful visual feedback. As was the case with the two sided hole, exchanging traditional force feedback with sensory substitution of force feedback made no difference in performance with an unobstructed view, but led to a performance decrement with an obstructed view.

8.3 Summary of Results for Time Delay Experiments

The objective of these experiments was to determine the usefulness and stability of using sensory substitution of force feedback in the presence of a time delay. These were experiments of major significance in this thesis, because performing the tasks with traditional force feedback in the presence of a time delay led to instabilities. Therefore, sensory substitution was tested as a possible solution to the instability problem that usually occurs when force information is presented in the presence of a time delay.

The peg-in-hole manipulation tasks with the four sided and two sided holes were repeated with a three second time delay (see Chapter 7). Since performing these tasks in the presence of a time delay with traditional force feedback led to instabilities, traditional force feedback was not tested.

8.3.1 Summary of Results for the Time Delay Experiments with the Simple Manipulation Task (Two Sided Peg-In-Hole Task)

The results for the time delay experiments conducted with the peg-in-hole task with the two sided hole are shown in figure 78.

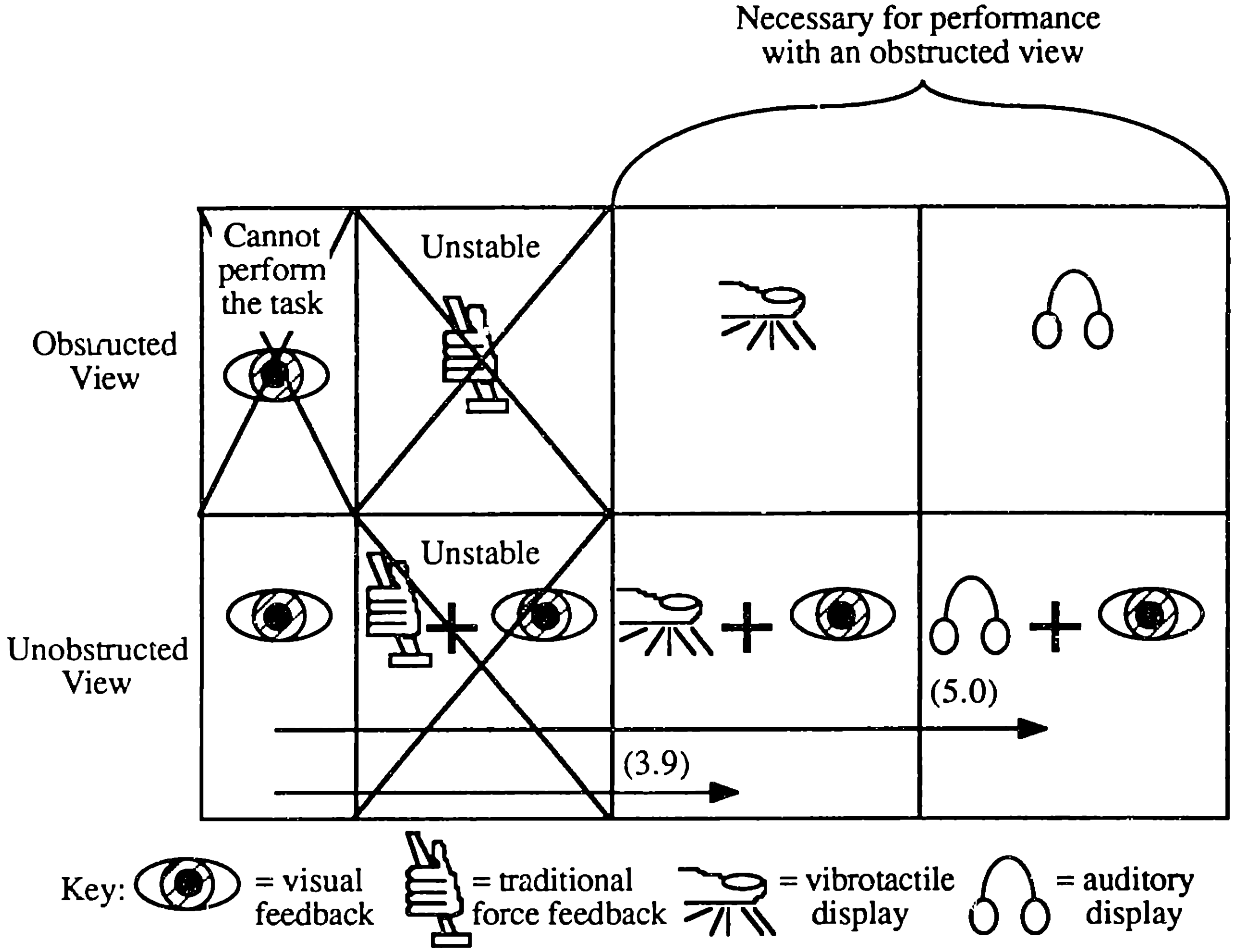

Figure 78 - Summary of Results for Time Delay Experiments with a Two Sided Hole (arrows indicate direction of significant performance improvement between two conditions; numbers indicate improvement in mean task time (seconds) between two conditions)

For performance with an unobstructed view, adding sensory substitution of force feedback to visual feedback improved performance as is displayed in figure 78. An analysis of the performance improvements with a time delay due to using sensory substitution will be discussed in Chapter 9.

When testing obstructed view performance, visual feedback alone would prevent the subjects from performing the task and was therefore not tested. Thus when testing time delay performance with an obstructed view, sensory substitution of force feedback provided the only method by which the task could have been completed.

8.3.2 Summary of Results for the Time Delay Experiments with the More Complex Manipulation Task (Four Sided Peg-In-Hole Task)

Figure 79 displays the time delay performance results for the peg-in-hole task with the four sided hole.

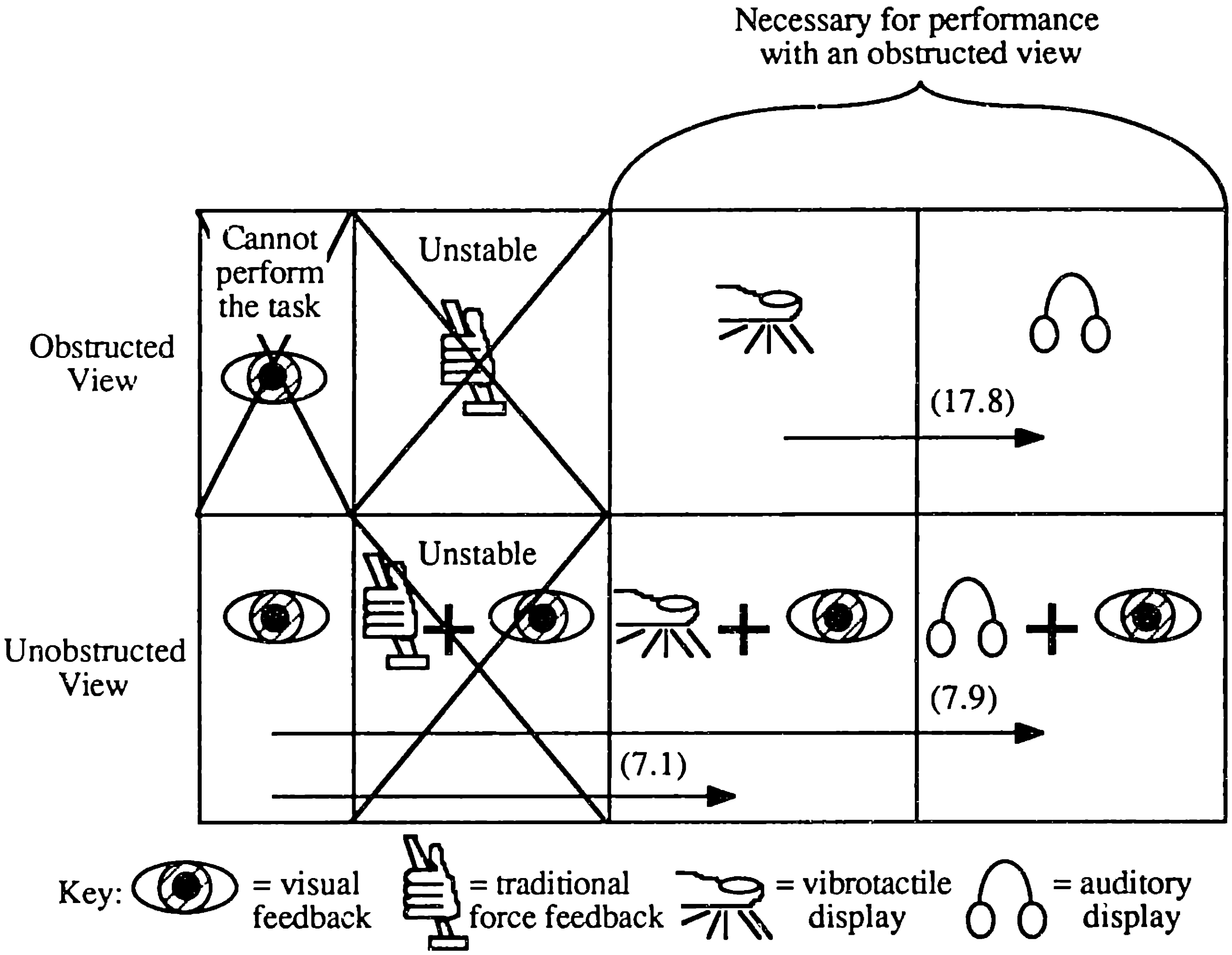

Figure 79 - Summary of Results for Peg-In-Hole Experiments with a Four Sided Hole (arrows indicate direction of significant performance improvement between two conditions; numbers indicate improvement in mean task time (seconds) between two conditions)

The results shown in figure 79 are in part similar the time delay results with the two sided hole (figure 78). With an unobstructed view, adding sensory substitution of force feedback to visual feedback improved performance. Further, when the view was obstructed, using sensory substitution of force feedback provided the only method by which the task could have been completed. However, unlike the two sided hole case, there was a significant performance difference between the vibrotactile and auditory displays for the obstructed view condition, with the auditory display providing significantly better performance. An explanation for this difference between the auditory and vibrotactile displays, based on the results of the psychophysical experiments on interpreting force direction information, is proposed in Chapter 10.

9. ANALYSIS OF SENSORY SUBSTITUTION

The objective of this chapter is to offer explanations as to why sensory substitution was helpful during some experimental conditions, and not helpful during others. The analyses provide a framework to help researchers and designers predict whether or not sensory substitution can aid performance in future applications. Previous chapters have presented and summarized the experimental procedures and results. However, the underlying theory as to why those results occurred was not presented. This chapter was written to provide a unifying explanation for all of the experimental results, and attempts to provide generality for the results. This should enable the results to be applied toward a wider variety of remote tasks than those investigated in this thesis.

In particular, this chapter analyzes the usefulness of sensory substitution for force feedback in combination with visual feedback, as compared to relying on visual feedback alone. The summaries presented in Chapter 8, displayed how sensory substitution was found to facilitate, degrade, or have no effect on operator performance when compared to using visual feedback alone. For example, sensory substitution was found to improve performance for the object contact, time delay, and obstructed view experiments. However, sensory substitution had no effect on performance during the two sided peg-in-hole experiments with an unobstructed view, and a negative effect on performance for the four sided peg-in-hole experiments with an unobstructed view.

In section 9.1, sensory information processing models are proposed to explain these results. The models focus on: 1) the quality of the visual feedback information, and 2) the complexity of the sensory substitution presentations of force information. These two characteristics were found to play decisive roles in whether or not sensory substitution was helpful to the test subjects. Following sections look deeper into the definitions and performance effects of degraded vision, time delay, and the complexity of sensory substitution. Additional experiments were conducted to further test the proposed models, and the results of these experiments are also presented in this chapter.

9.1 General Descriptive Models of the Effects of Sensory Substitution

This section contains models which describe with generality, how the quality of the visual feedback and the complexity of the sensory substitution information affected operator performance.

9.1.1 Model for Clear Visual Conditions

Sensory substitution was found in some of the experiments to have no effect on performance when added to visual feedback. This model proposes that given clear visual conditions and simple sensory substitution presentations of force information, visual feedback alone provided the human operator with adequate information. Therefore, the addition of information through a non-visual channel did not have an effect on performance. This scenario is displayed in figure 80.

Clear visual feedback conditions are defined as having all of the following three characteristics:

1) there was an unobstructed view, and

2) the critical movements for the task were in directions which were easily discriminable with the available visual feedback, and

3) there was no time delay.

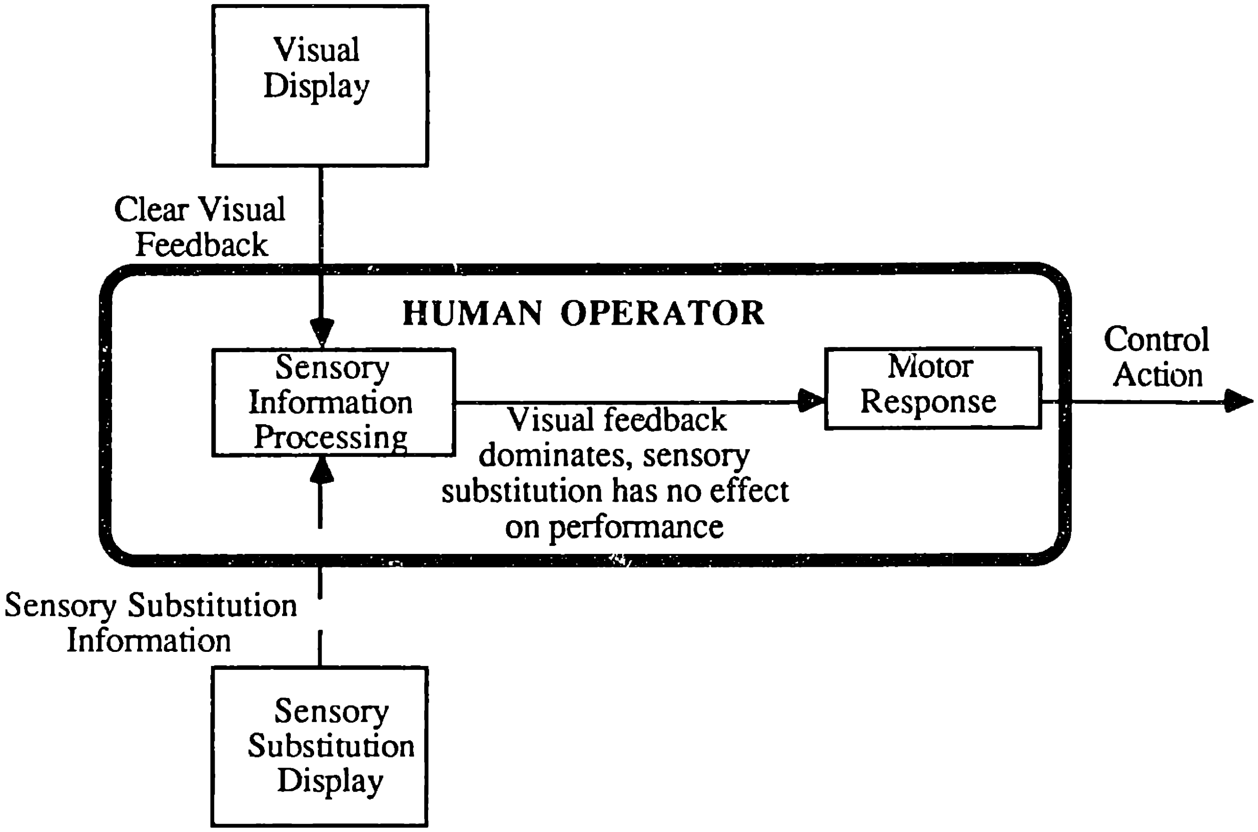

Figure 80 - Integration of Sensory Substitution with Clear Visual Conditions and Simple Sensory Substitution Presentations

Simple sensory substitution presentations of force information are defined as those which represented forces that consisted of only one component. These representations existed for the object contact experiments, in which the force was present only along one dimension. Simple presentations also existed for the peg-in-hole tasks with the two sided hole, during which the position of the force in the hole was represented as existing only on either of the two sides of the hole. During these tasks, it required a minimal amount of information in order to determine the position of the forces, as is explained further in the next few paragraphs.

For the experiments on object contact force, the position of a force existed only in one dimension. Therefore the very existence of a force indicated that the position of the force was on a target object. Using information theory, zero bits were needed to identify the force position.

During the peg-in-hole experiments with the two sided hole, the force from the peg onto the hole could have been acting on either the right or on the left side of the hole. In information theory terms, these two possibilities for force position would require one bit of information in order for the human operator to accurately interpret the force's position. These representations of force position through sensory substitution are defined as simple.

As will be explained in upcoming sections of this chapter, the combination of clear visual conditions and simple sensory substitution presentations of force information depicted in figure 80 existed in only one experimental scenario: the peg-in-hole task with the two sided hole, without a time delay, and with an unobstructed view.

9.1.2 Model for Degraded Visual Conditions

During other experiments, sensory substitution was found to significantly improve performance when presented in combination with visual feedback. To explain these results, a model for degraded visual conditions is proposed. If the visual conditions were not clear but were degraded in some way, performance was improved when information through sensory substitution was added to the visual feedback as is shown in figure 81. Degraded visual feedback existed if any one of the following three conditions existed:

1) there was an obstructed view, or

2) the critical movements for the task were in directions that were not clearly represented by the visual display (for example, depth perception), or

3) there was a time delay

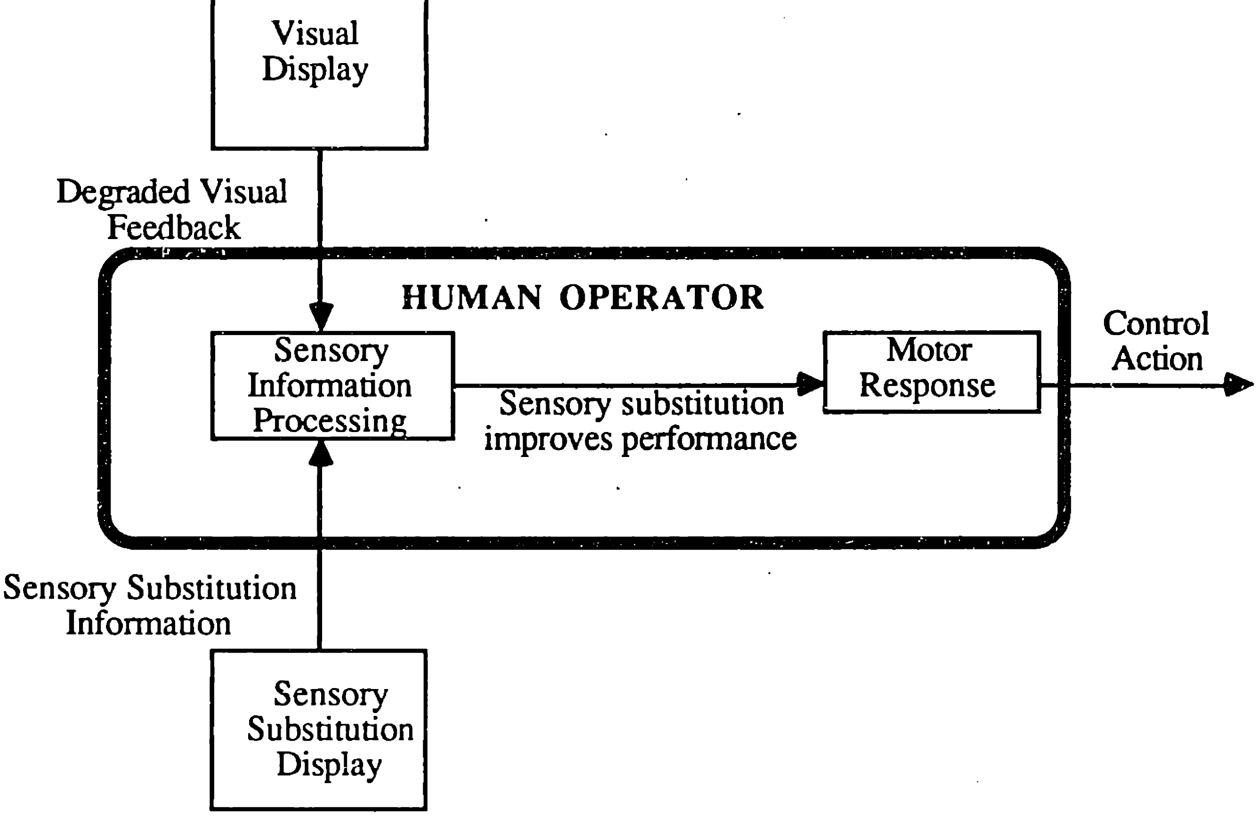

Figure 81 - Integration of Sensory Substitution with Degraded Visual Conditions

Each of the degraded visual feedback conditions is examined in detail in future sections of this chapter. Degraded visual feedback due to an obstructed view will be discussed in section 9.3, degraded visual feedback due to depth perception is discussed in section 9.2, and degraded visual feedback due to time delay is analyzed in section 9.4.

9.1.3 Models for Complex Sensory Substitution Presentations of Force Information

During other experimental conditions, sensory substitution led to degraded performance when presented simultaneously with visual feedback. The model to explain these results proposes than an investigation of the complexity of the information presented to the human operator can help determine when sensory substitution can degrade performance. If the visual conditions were clear but the sensory substitution presentations of information were complex, sensory substitution could divide the operator's attention, distract the operator, and degrade performance (see figure 82).

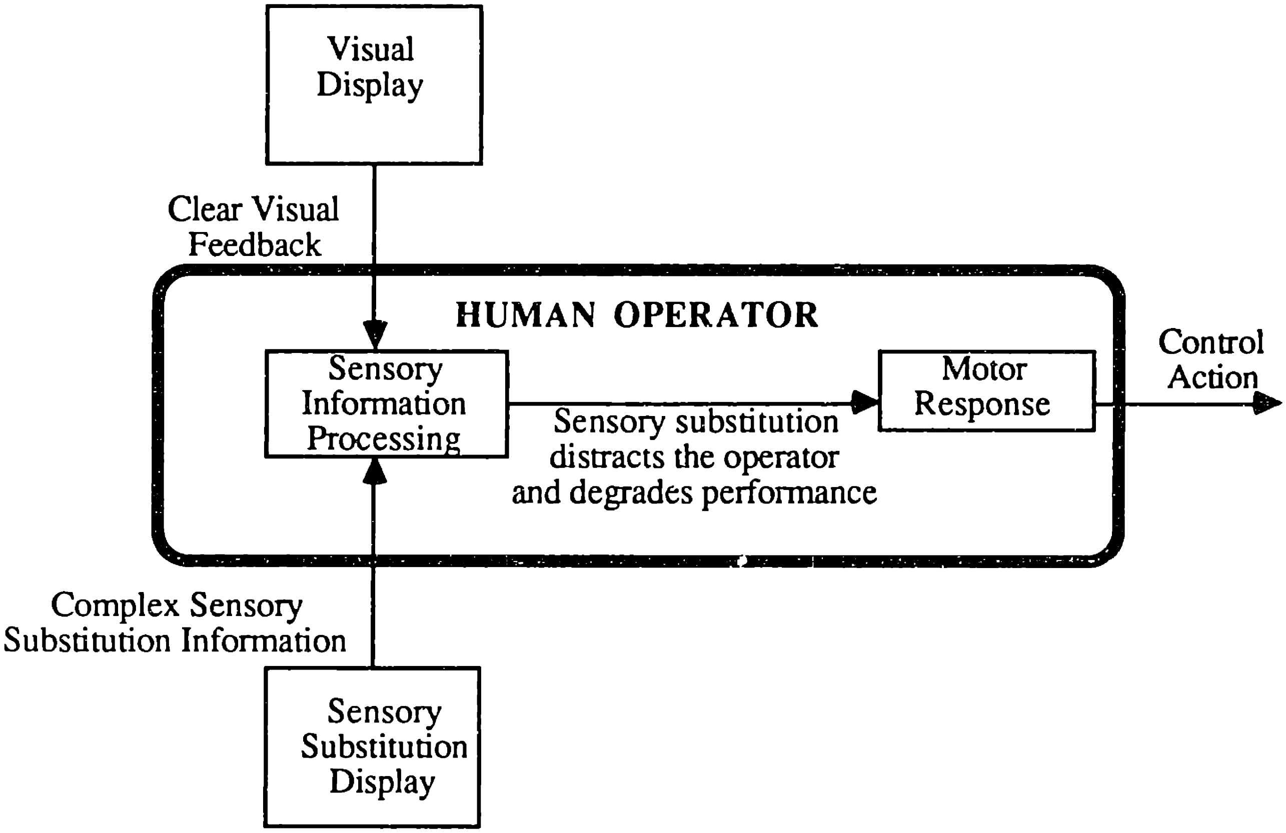

Figure 82 - Integration of Sensory Substitution with Clear Visual Conditions and Complex Sensory Substitution Presentations

Complex sensory substitution presentations of force information are defined as those which represented forces that could consist of more than one component. Such presentations were possible during the peg-in-hole experiments with the four sided hole. During these tasks, the force to be interpreted could have been located on any combination of the four sides of the hole. The force could have existed on one of the four sides alone, or on combinations of the top side with the left or with the right side, or on combinations of the bottom side with the left or with the right side. Therefore at least eight different combinations of sides existed on which the force could have been acting. Taking these eight possible positions and applying information theory, it was calculated that three bits of information (2^3 = 8 alternatives) would have been needed for the human operator to consistently identify the direction of the force accurately. Therefore when performing the task with the four sided hole, more information was available to be input into the human operator (3 bits) than the amount of available input information associated with the two sided hole task (1 bit). This difference in input information was the difference in the force presentations being defined as simple (two sided hole) or complex (four sided hole). An analysis of the effects of the complexity of the sensory substitution force presentations on performance is presented in section 9.6.

9.1.4 Overall Model of the Effects of Sensory Substitution

Putting the pieces shown in figures 80 through 82 together, a unifying model is proposed. This model is displayed in figure 83, and indicates when sensory substitution was and when it was not helpful to the human operator.

Figure 83 depicts the human operator as concurrently receiving information from the visual and sensory substitution displays. The initial sensory processing block in figure 83 shows that the operator differentiated between clear or degraded visual feedback, and between complex or simple sensory substitution presentations. The effect that sensory substitution information had on performance was largely dependent on the quality of the visual feedback, as is depicted by the upper question diamond in figure 83. If the visual feedback was not poor and was not delayed, clear visual feedback existed and the usefulness of sensory substitution would depend upon the complexity as is depicted in the lower question diamond. If the sensory substitution were not complex, i.e. the forces could consist of only one component and the amount of available input information to the human operator to convey the direction of the force through sensory substitution was one bit or less, sensory substitution would have no effect on performance. However if the sensory substitution were complex, i.e. the force could consist of more than one component and the amount of available input information to indicate the direction of the force was three bits or more, sensory substitution could hinder performance.

If, however, the answer to the upper question diamond was yes, then visual feedback was poor or delayed. In these cases, the processing of sensory substitution information improved performance.

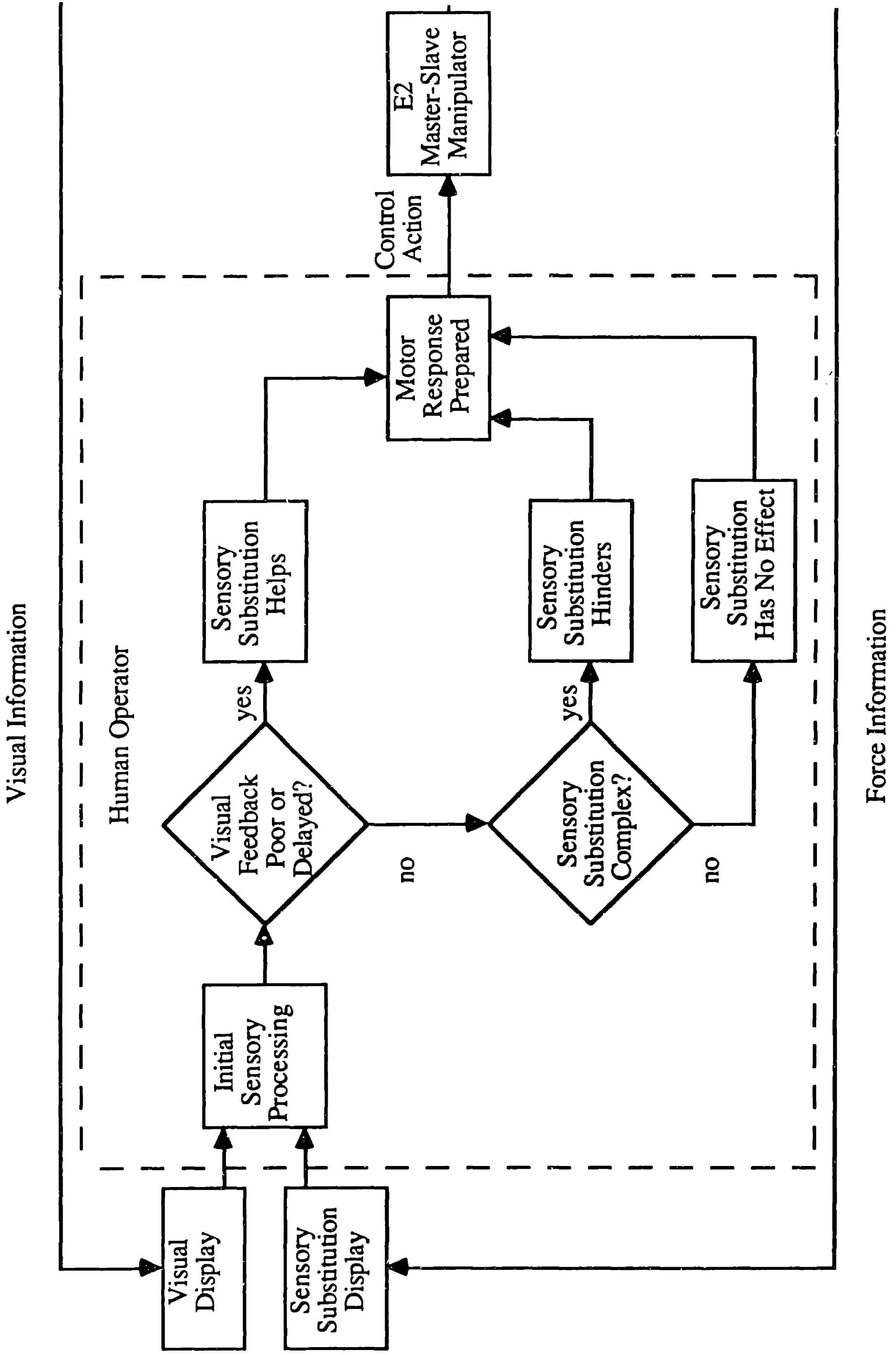

Figure 83 - Integration of Sensory Substitution with Visual Feedback for Teleoperated Tasks

The performance diagrams shown in figures 80-82 can be explained in another way. Let us examine changes in performance, as a function of increases in the total amount of information through both the visual and auditory displays presented to the operator. As this amount of information increased, operator performance also generally increased. However if the amount of information became excessive, operator performance could also decrease.

For example, consider the peg-in-hole task with the four sided hole and the variety of task conditions under which it was performed. The most difficult of these conditions was the existence of a time delay combined with an obstructed view, and this difficulty was reflected in the associated high mean task times. The results from the time delay and obstructed view scenario showed that the auditory display provided superior task performance compared to the vibrotactile display. These task performance results correlated to the results of the psychophysical force position tests, which showed that the auditory display conveyed more information to the operator than the vibrotactile display.

For time delay tests with an unobstructed view, performing the task with sensory substitution combined with visual feedback led to significantly better task performance than performing the task with visual feedback alone. This again correlated to what would be expected from the amount of information provided to the operator, since the addition of sensory substitution increased the amount of information available to the human operator.

This trend generally continued until the criteria for clear visual feedback, i.e. no time delay and an unobstructed view, were examined. Under the clear visual feedback conditions, the addition of information through sensory substitution did not improve performance. Further, the trend was reversed when the auditory display in combination with visual feedback led to significantly higher task times than using the visual display alone. This was in spite of the fact that the amount of information presented to the operator was increased.

9.2 Degraded Visual Feedback Due to Depth Perception

Each of the conditions that led to degraded feedback will be analyzed further in the next few sections of this chapter. This section analyzes the effects of depth perception, and explains the results observed during the object contact tasks.

The results for the object contact experiments showed that performance was significantly better when visual feedback was combined with either of the sensory substitution displays, compared to when visual feedback was used alone. During these tasks, visual feedback was degraded in providing information about the task to the human operator, even though the view of the target objects was unobstructed. The visual feedback was degraded due to the importance of depth perception when performing these tasks, and the inability of visual feedback to present depth perception clearly to the operator through the two dimensional visual display. The direction straight ahead from the operator, along the line of sight of the camera has been defined as the z-direction (see figure 84). Perception of movement in the z-direction (depth direction) was critical for these tasks because the subjects detected whether or not they successfully contacted a target object through movement in the z-direction. Further, penalties for excessive movement were assessed for applying too much force in the z-direction. Therefore, knowing the position of the manipulator in the z-direction was critical during task performance. Translational movement along this z-direction axis has been shown in previous research to be significantly more difficult than movement along the other two translational directions [Massimino, Sheridan, and Roseborough, 1989], and could have affected the outcome of the object contact force experiments.

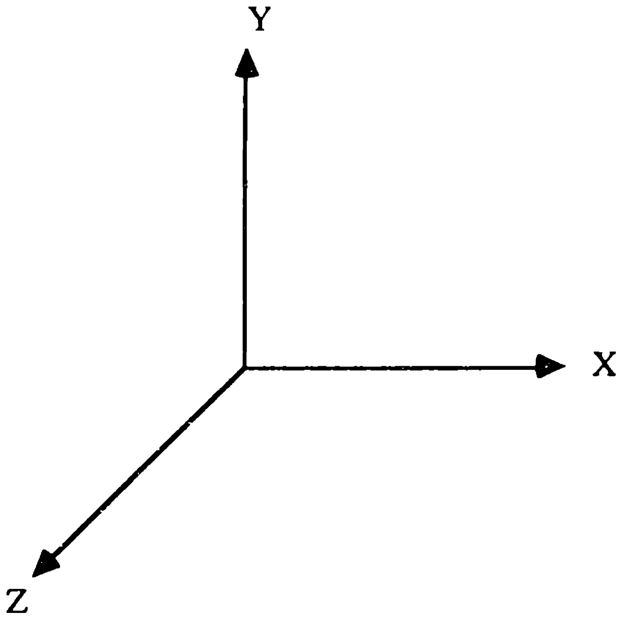

Figure 84 - Definition of Translation Directions for Manipulation Tasks

The object contact and peg-in-hole tasks were related somewhat to pursuit tracking tasks [Sheridan and Ferrell, 1974]. The subjects were able to see both the tip of the E2 end effector (the controlled object) and the object or the hole (the target objects) and were trying to correctly position the E2 with respect to the object or to the hole. A previous study [Massimino, 1990] examined the abilities of human operators to track objects in six degrees of freedom (dof) during pursuit tracking tasks. The three translational directions were compared for relative amounts of root mean square error (rmse) accumulated while tracking a target object with a controlled object. Each direction, or dof, was initially tested independently, one at a time, with the target and controlled objects moving in only one direction. In later, more advanced tests, the rmse was calculated for each degree of freedom (dof) while the subjects tracked the target with the controlled object for movement in all six degrees of freedom simultaneously. The results for each translational direction while tracking in one dof at a time are shown in figure 85, and the results for each translational direction while tracking in all six dof at a time are shown in figure 86. For both the one dof and six dof tracking scenarios the z-direction (normal to the video monitor screen surface) produced significantly more error ($F(2,10)=39.83$, $p<0.0001$ for one dof tracking, F(2,6)=77.94, p<0.0001 for six dof tracking) than the other two translational degrees of freedom.

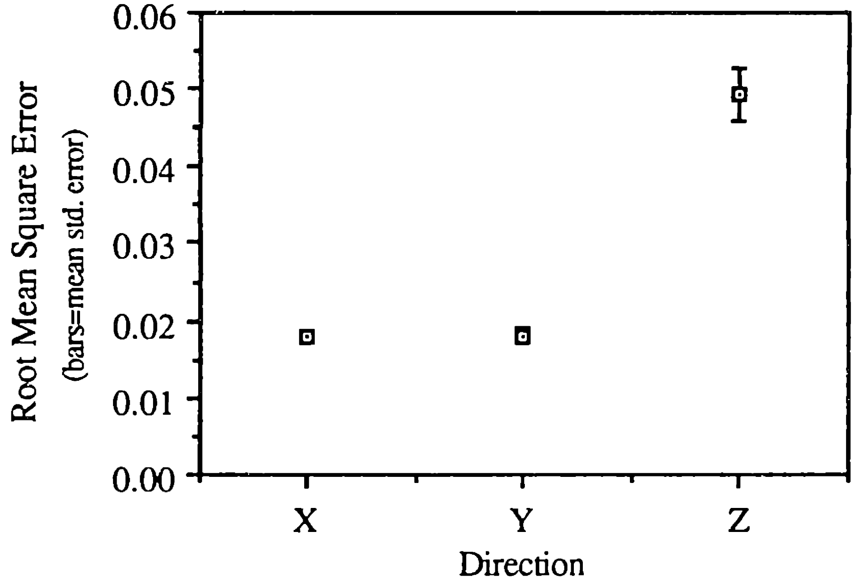

Figure 85 - Results for Tracking in One Degree of Freedom at a Time
Source: [Massimino, 1990]

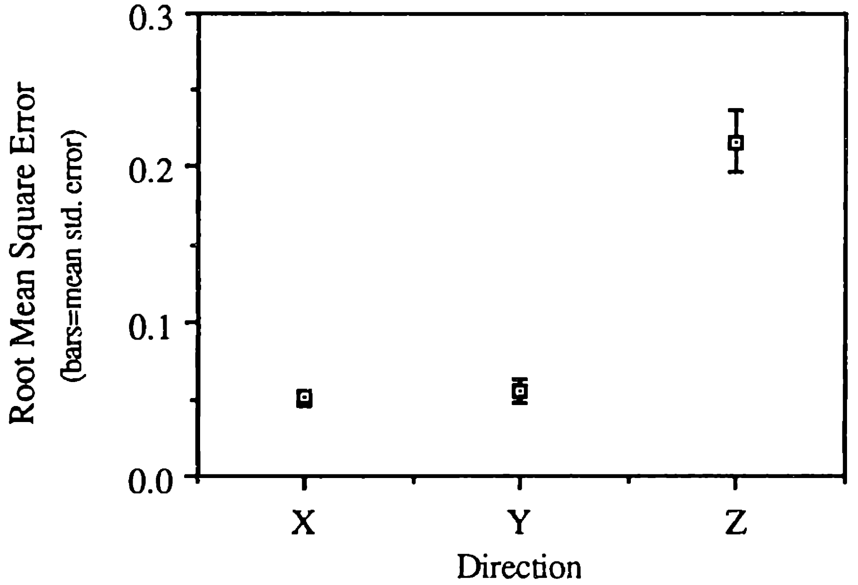

Figure 86 - Results for Tracking in Six Degrees of Freedom Simultaneously
Source: [Massimino, 1990]

The results in figures 85 and 86 show that tracking movement along the z-direction was significantly more difficult and resulted in poorer tracking performance than tracking movement along the x or y-directions. The problems that subjects had with z-translation when compared to either x-translation or y-translation, were probably due to changes in z-translation appearing to the subject as a change in size on the two dimensional display. This change in size was due to the z-axis being the axis coming out of the display screen making z-translation a movement of coming out of and into the screen. Conversely, both y-translation and x-translation represented changes in position of the objects. Thus it appears that a change in position of a target on the screen was easier to determine and track than changes in size due to the difficulty with perceiving depth.

These tracking results presented above, can help to explain the performance differences found during the object contact tasks. Since an important axis of movement during the object contact tasks for the test subjects was the z-translation axis, the subjects had difficulty in interpreting the depth position of the manipulator, determining whether or not contact had been made with the target object, and judging if contact was excessive and would incur a penalty when relying solely on visual feedback. As the tracking task results showed, perceiving movement in the z-direction visually was inferior compared to visual perception in the other translational directions. Therefore, during the object contact tasks, the subjects were not able to clearly perceive the position of the slave arm in relation to the target objects, and additional information in the form of a auditory or vibrotactile cue helped the operator to perceive contact and improved task performance.

A diagram of the manual control system when vision was degraded due to the need to accurately perceive depth cues, illustrating that subjects successfully integrated visual feedback and sensory substitution to improve performance, is show in figure 87.

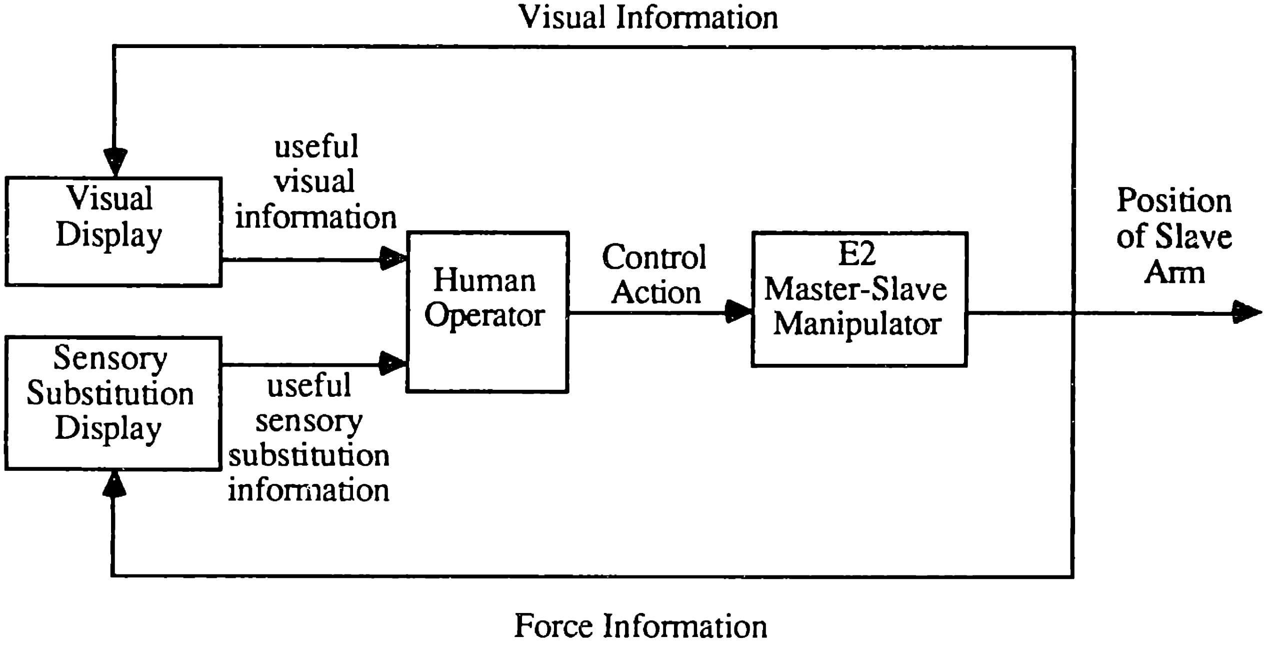

Figure 87 - Manual Control System for Degraded Vision Due to Depth Perception

9.3 Degraded Visual Feedback Due to Obstructed Views

The second visual condition that was found to degrade the visual feedback was obstructed views. This section analyzes how sensory substitution assisted the test subjects to perform tasks with obstructed views.

Some of the manipulation tasks in this thesis were conducted with totally obstructed views. When the view was fully obstructed, the visual display was not at all useful, and the subjects were in need of feedback through non-visual sensory channels in order to perform the task. Sensory substitution enabled the task to be performed successfully without reliance on visual feedback or traditional force feedback. This was an extreme condition of poor visual feedback, since the task was impossible to perform if one were to rely on visual feedback alone. The manual control system for performance with an obstructed view is displayed in figure 88 and shows that the subject was entirely dependent on sensory substitution information in order to perform the task.

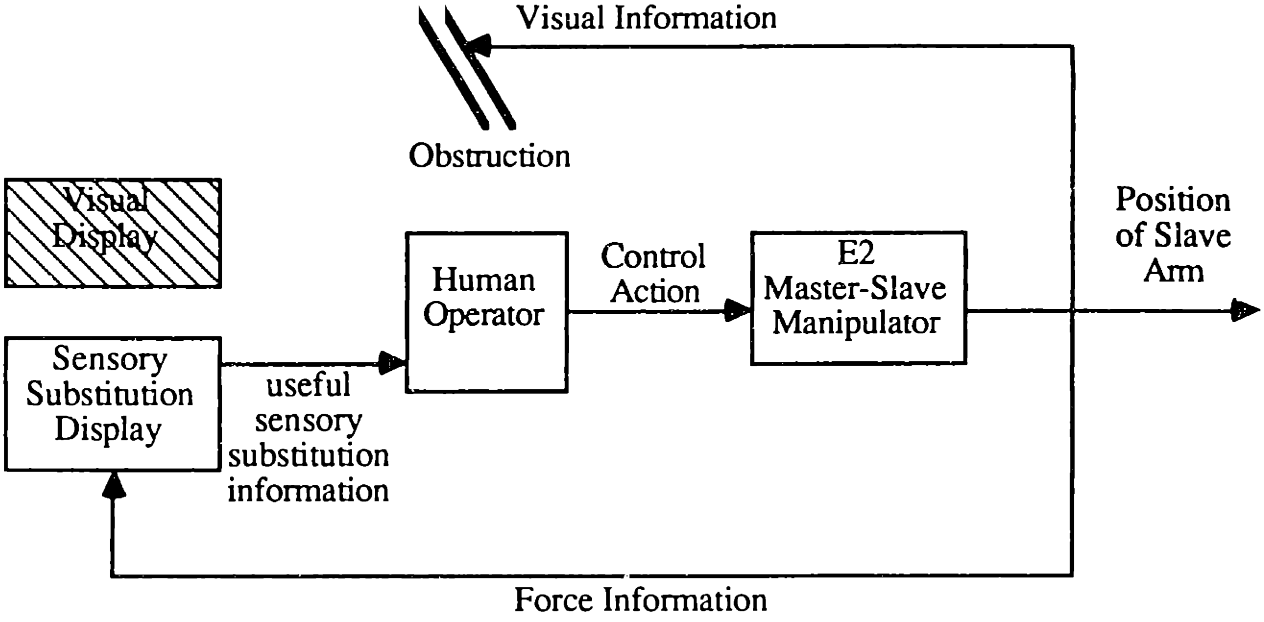

Figure 88 - Manual Control System for Degraded Vision Due to an Obstructed View

9.4 Degraded Visual Feedback Due to Time Delay

This section analyzes the effects that a time delay had on presenting the test subjects with sensory substitution. Explanations are proposed concerning why sensory substitution was helpful during the peg-in-hole tasks conducted in the presence of a time delay, even when the view was not obstructed. These results were different than those observed for the same tasks performed without a time delay, during which sensory substitution did not assist the operator when the view was not obstructed.

The analysis of these results has found that the test subjects' abilities to interpret visual feedback were degraded by the presence of a transmission time delay. This degradation made the simultaneous presentation of information through another sensory modality helpful in performing tasks as was summarized in Chapter 8, figures 78 and 79. It also produced results that were much different than the results obtained when the task was performed without a time delay, and vision alone was able to maximize performance (Chapter 8, figures 76 and 77).

The time delay made the test subjects wait for three seconds for feedback on the results of their control inputs. The move and wait strategy employed when operating with a time delay, made relying on visual information more difficult when trying to determine the position of the manipulator and perform the task. Subjects commented that when performing the tasks with a time delay, visual feedback was useful for gross positioning of the peg near the hole. However, fine positioning of the peg was critical in order to insert the peg into the hole, and was difficult when only having visual feedback. Sensory substitution helped with this fine positioning of the peg, and therefore complimented visual feedback. Therefore, the utility of sensory substitution for peg-in-hole tasks increased in the presence of a time delay, and the time delay produced a degraded visual environment. Visual feedback alone was not as useful to the operator as it was without time delay, and force information through sensory substitution which supplemented vision improved performance.

Warrick [1949] studied the effects of time delays on tracking tasks which were dependent on visual feedback. He found that even minimal delays of 0.04 seconds, delays imperceptible to the human operator, decreased performance for compensatory tracking tasks (see figure 89). For pursuit tracking tasks, Wallach [1961] found similar results.

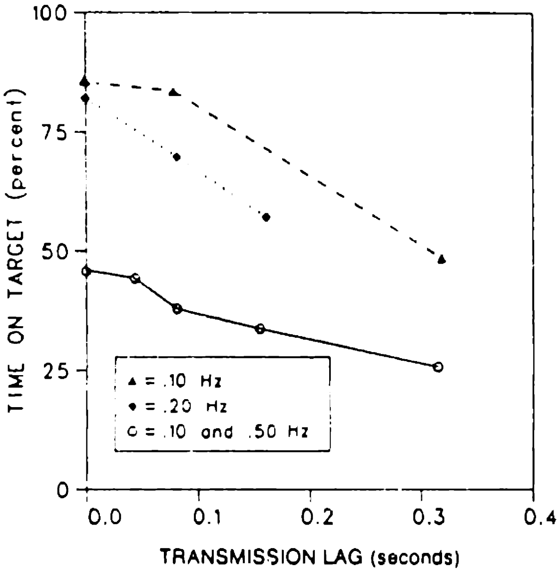

Figure 89 -Tracking Accuracy as a Function of Delay Time
Source: [Wickens, 1986, from Warrick, 1949]

Time delay has also been shown to affect a human operator's subjectively perceived difficulty of a visually oriented tracking task. As the length of a time delay increased, the operator had to allow for more lead time to compensate for the time delay. Ashkenas [1965] found that pilots considered tracking more difficult as the time delay increased and as a result had decreasing opinion ratings of the task. These trends were studied further by McRuer and Jex [1967], and their results based on the data collected by Ashkenas [1965] are shown in figure 90. These subjective rating results provided further evidence that the presence of a time delay can adversely affect a human operator's ability to interpret visual information, and impede performance of a task that is heavily dependent on visual information for successful completion.

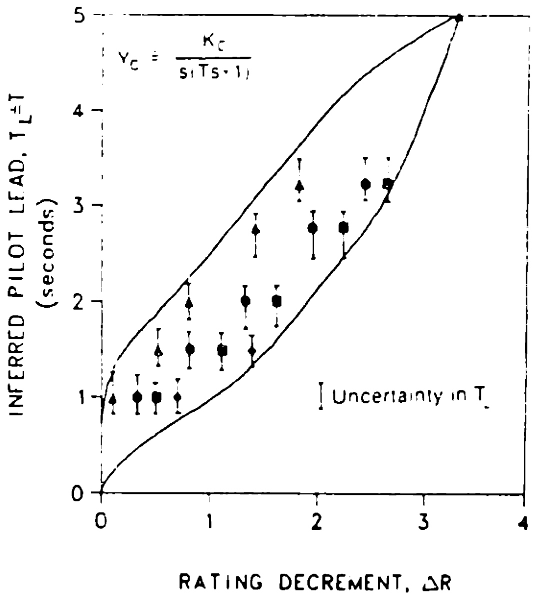

Figure 90 - Pilot Lead Time Constant Versus Pilot Opinion Rating
Source: [Wickens, 1986, from McRuer and Jex, 1967]

Both the experimental (figure 89) and subjective (figure 90) results indicated that time delay can degrade a human operator's ability to perform tracking tasks, when visual feedback is the primary source of information. These studies demonstrated that a time delay can negatively impact a human operator's ability to perceive visual information, and therefore lead to a degraded visual environment. This degraded visual environment due to time delay, like the degraded environments due to depth perception and obstructed views, made the presentation of force information through sensory substitution beneficial for the human operator even though the sensory substitution feedback was also delayed. Figure 91 shows the manual control system for operation with a time delay, indicating that sensory substitution can be successfully used by the human operator to improve time delay performance.

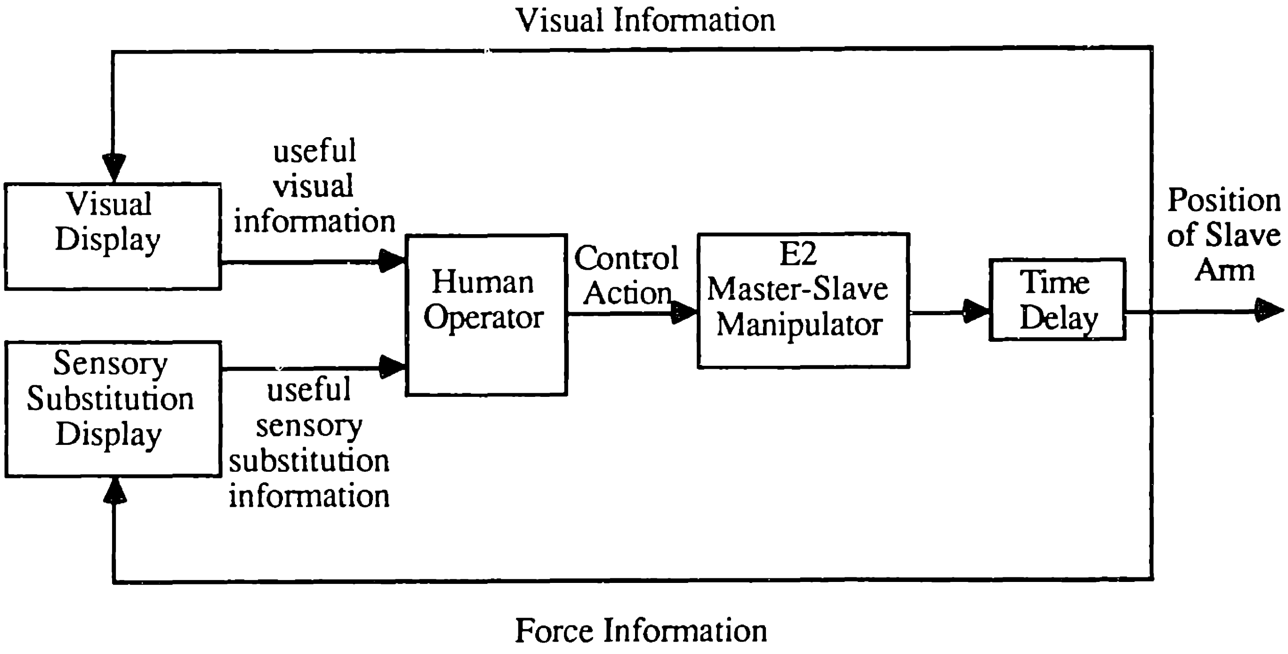

Figure 91 - Manual Control System for Degraded Visual Feedback Due to the Presence of a Time Delay

These time delay results can also be characterized by the bisensory information processing model proposed by Oatman [1975] that was discussed in section 2.5.4 of this thesis. This theory stated that as tasks become increasingly difficult due to stimulus signals becoming more difficult to detect, recognize, or discriminate, presentation of the information over more than one sensory modality had been observed to improve performance. When operating with a time delay, the task became more difficult than when operating without a time delay. Further, it became more difficult to quickly and efficiently detect the position of the peg with respect to the hole when only having visual feedback. Therefore, visual feedback no longer provided enough information to the operator, and performance was not maximized by only using visual feedback. Applying Oatman's theory, it appeared as though the human operator required more information in the presence of a time delay to perform the task than was necessary without a time delay. Therefore presenting task information over more than one sensory modality improved operator performance.

9.5 Additional Visual Parameters Which May Affect Performance

Other visual parameters which were not formally tested, but could lead to a degraded visual environment, may also affect the usefulness of sensory substitution. These parameters include frame rate, resolution, grayscale, subtended visual angle and the camera viewpoint. For example, Ranadive [1979] studied tradeoffs involving varying video frame rate, resolution, and grayscale for telemanipulation. He found that reducing any of these three parameters could significantly degrade teleoperation performance. The results outlined in the previous sections suggest that sensory substitution may be able to improve performance when the degraded visual feedback conditions studied by Ranadive are present.

Investigating the effects of force feedback to make up for degradations in visual feedback due to low frame rates when using a video monitor for visual feedback, a previous investigation found that traditional force feedback provided for a significantly larger improvement in performance at low frame rates (3 frames/second) than it did at higher frame rates (30 frames/second) [Massimino, 1988]. For direct viewing of teleoperated tasks, previous research also found that as the the size of the subtended visual angle for the remote object to be manipulated decreased, due to increases in the viewing distance, force feedback improved performance at an increasing rate [Massimino, 1988]. Therefore as the visual feedback became increasingly degraded, force information became increasingly more important for improving task performance. These findings parallel the results found in this thesis. Therefore one can expect that with conditions such as lower frame rates or lower subtended visual angles, sensory substitution could significantly improve performance.

Exploring the theory that the value of sensory substitution was dependent on the quality of the visual feedback, two additional experiments were conducted: 1) experiments on decreased visual resolution, and 2) experiments on a partially obstructed view. The results of these experiments are discussed in sections 9.5.1 and 9.5.2.

9.5.1 Degraded Visual Feedback Due to Decreased Resolution

To further test the hypothesis that degraded visual conditions would lead to an increase in the utility of sensory substitution, additional experiments were conducted. The primary objective was to obtain additional information that would help to verify or reject the models proposed in this thesis for general applicability to a variety of visual conditions.

The first of these experiments, tested the effects of a degraded visual environment due to decreased resolution of the visual feedback. To decrease the resolution of the visual signal, the camera was set out of focus and an opaque layer of plastic was placed on the camera lens. The hole was then barely visible through the blurred video scene. This simulated what would happen if teleoperation took place in a murky undersea environment, or if the resolution quality of a video link was poor. These conditions were examined to further test the hypothesis that the value of sensory substitution for telemanipulation was dependent on the quality of the visual feedback.

The four sided peg-in-hole task was performed just as it was previously described in section 6.2. Ten experimental trials for each feedback condition were recorded by one subject after adequate training. Four feedback conditions were tested: 1) blurred visual feedback alone, 2) blurred visual feedback plus traditional force feedback, 3) blurred visual feedback plus sensory substitution of force feedback through the auditory display, and 4) blurred visual feedback plus sensory substitution of force feedback through the vibrotactile display. The results are shown in table 19 and figure 92.

Feedback Condition	Mean Task Time (sec.)
Visual Feedback with Poor Resolution Alone	9.07
Visual Feedback with Poor Resolution plus Traditional Force Feedback	2.58
Visual Feedback with Poor Resolution plus Sensory Substitution of Force Feedback through the Vibrotactile Display	4.73
Visual Feedback with Poor Resolution plus Sensory Substitution of Force Feedback through the Auditory Display	4.51

Table 19 - Results for Manipulation Experiments with a Poor Visual Resolution

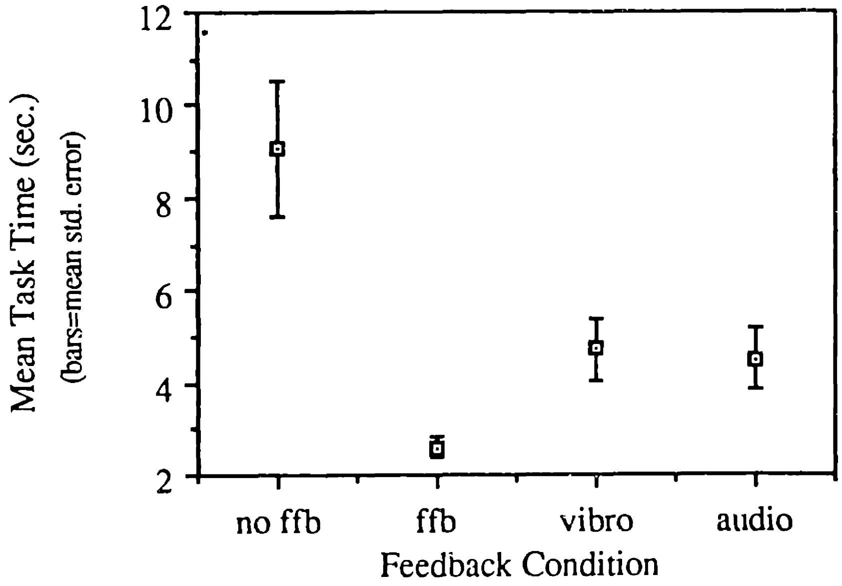

Figure 92 - Results for Manipulation Experiments with Poor Visual Resolution

A series of paired t-tests showed that using visual feedback with poor resolution alone produced significantly higher mean task times than combining blurred vision with traditional force feedback (t(9)=4.63,p<0.001), or with sensory substitution of force feedback through the auditory display (t(9)=2.71,p<0.05), or with sensory substitution of force feedback through the vibrotactile display (t(9)=3.03,p<0.05). In addition, using traditional force feedback led to significantly better performance than using either of the auditory display (t(9)=2.52, p<0.05) or the vibrotactile display (t(9)=4.17,p<0.05). There was no significant difference between the performance results for the auditory or vibrotactile displays.

These results are similar to those observed for the four sided peg-in-hole task with degraded visual feedback due to an obstructed view. Therefore, these experiments, conducted with degraded visual feedback due to poor visual resolution, reinforce the hypothesis that the utility of sensory substitution will increase as the quality of the visual feedback becomes degraded.

9.5.2 Degraded Visual Feedback Due to a Partially Obstructed View

A second additional experiment was conducted to further test the hypothesis that the utility of sensory substitution would increase with degraded visual feedback. This section discusses these experiments, which were conducted with a partially obstructed visual view of the remote site. This partially obstructed provided a visual environment not tested during the major experiments of this thesis. It also allowed the further testing of the usefulness of sensory substitution with a different type of degraded visual feedback.

An additional objective existed for conducting these experiments. The peg-in-hole experiments described earlier, were initially conducted with totally obstructed and unobstructed views. However, the effects of sensory substitution on a partially obstructed view were not initially investigated. To test partially obstructed views, the four sided peg-in-hole tests were conducted with a partially obstructed view. Only the hole itself and a small area surrounding the hole was obstructed from view. With this view, the operator was able to pick up enough visual cues from the remote site to determine the position of the remote manipulator, and successfully complete the task. The totally obstructed and unobstructed views tested earlier in the thesis represented polarized test points. These partially obstructed view tests had a secondary goal, of determining some performance characteristics for obstructed visual conditions in between the two end points previously tested.

One test subject performed these experiments, and after training, ten experimental trials were conducted for each of the four experimental conditions: 1) partially obstructed visual feedback alone, 2) partially obstructed visual feedback plus traditional force feedback, 3) partially obstructed visual feedback plus sensory substitution of force feedback through the auditory display, and 4) partially obstructed visual feedback plus sensory substitution of force feedback through the vibrotactile display. The results are shown in table 20 and figure 93.

Feedback Condition	Mean Task Time (sec.)
Partially Obstructed Visual Feedback Alone	10.6
Partially Obstructed Visual Feedback plus Traditional Force Feedback	2.82
Partially Obstructed Visual Feedback plus Sensory Substitution of Force Feedback through the Vibrotactile Display	4.27
Partially Obstructed Visual Feedback plus Sensory Substitution of Force Feedback through the Auditory Display	3.57

Table 20 - Results for Manipulation Experiments with a Partially Obstructed View

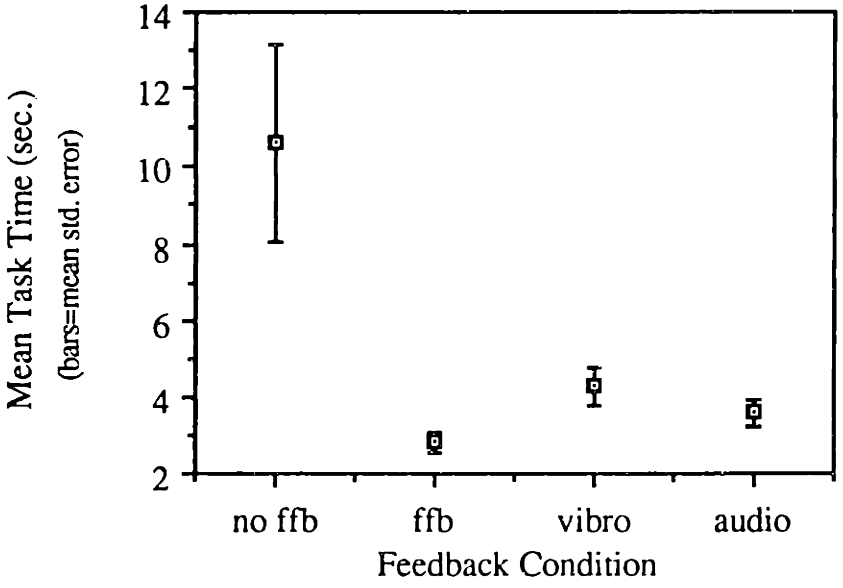

Figure 93 - Results for Manipulation Experiments with a Partially Obstructed View

A series of paired t-tests showed that using partially obstructed visual feedback alone produced significantly higher mean task times than combining partially obstructed vision with traditional force feedback ($t(9)=3.05, p<0.05$), or with sensory substitution of force feedback through the auditory display ($t(9)=2.73, p<0.05$), or with sensory substitution of force feedback through the vibrotactile display ($t(9)=2.46, p<0.05$). In addition, using traditional force feedback led to significantly better performance than using either of the auditory display ($t(9)=3.18$, $p<0.05$) or the vibrotactile display ($t(9)=3.11, p<0.05$). There was no significant difference between the performance results for the auditory or vibrotactile displays.

Unlike the totally obstructed view tests, visual feedback alone could be tested with a partially obstructed view. The results for the four sided peg-in-hole task with a partially obstructed view were similar to those obtained for the totally obstructed view and the blurred view scenarios because sensory substitution improved performance over visual feedback alone, but was not as effective as using traditional force feedback. The comparison of sensory substitution of force feedback to traditional force feedback will be explored in Chapter 10.

It is reasonable to conclude that lesser degrees of obstruction would lead to performance results closer to those obtained for the unobstructed view tests, until there was no significant difference between using visual feedback alone and adding on sensory substitution of force feedback. In addition one would also expect that increasing the amount of obstruction for the partially obstructed view would lead to a widening of performance differences between visual feedback alone and adding on sensory substitution of force feedback. This would continue until using visual feedback alone made it impossible to perform the task successfully.

Although the partially obstructed view experiment did not measure all degrees of obstruction, it did show that the usefulness of sensory substitution can be affected by varying the degree of obstruction. It also provided a data point in between the previously tested conditions of totally unobstructed and totally obstructed views. Further, these experiment reinforced the hypothesis that the usefulness of sensory will increase as the quality of the visual feedback available to the human operator becomes degraded.

9.6 Complexity of Sensory Substitution Presentations of Force Feedback

The next sections (9.6.1 - 9.6.2) do not analyze the effects of degraded visual feedback on the utility of sensory substitution as did previous sections. Instead, this section analyzes the effects of the complexity of, and the amount of information transmitted to the human operator by, the sensory substitution displays in determining the utility of sensory substitution. Clear visual feedback, as was defined in section 9.1.1, is assumed throughout the analysis presented in these sections.

The data presented in figures 85 and 86 of section 9.2 indicated that for translational movements that did not involve depth perception, i.e. movements in the x or y-translational directions, the subjects were able to track the target with significantly better accuracy than movements that did involve depth perception. Therefore visually interpreting changes in x and y positions of a target was easier than interpreting changes in depth.

For the peg-in-hole tasks, the critical part of the task was to correctly position the peg with respect to the hole in the x,y positions in order to successfully complete the task. Once the peg was lined up correctly, task completion was dependent on feeling the edges of the hole in order to insert the peg completely, and not on depth perception. In addition, there was no assessed penalty for excessive movement in the z-direction as there was for the object contact experiments. Therefore the perception of depth was not critical, whereas the perception of up and down and side to side positioning was important. These critical positions were clearly represented and detectable with visual feedback as was shown by the tracking tasks (figures 85 and 86).

This clear visual presentation of critical task information made it possible for the subjects to easily complete the peg-in-hole tasks with an unobstructed view, and the addition of information through sensory substitution was not helpful in performing the task. However, what did make a difference in the usefulness of sensory substitution during the peg-in-hole tasks, was the complexity of the force presentations from each of the sensory substitution displays. The effects of the complexity of the force presentations on the usefulness of sensory substitution will be analyzed in the following sections.

9.6.1 Simple Sensory Substitution Presentations of Force Information

First, let us examine the effects of less complex, or simple, presentations of force information through sensory substitution. These types of presentations were found not to impede or aid performance with clear views, and the reasons behind those findings are analyzed further in this section.

Simple sensory substitution presentations of force information were defined as those which represented forces that consisted of only one component. These types of presentations existed for the object contact experiments, in which the force was present only along one dimension. They also existed during the peg-in-hole tasks with the two sided hole, during which the position of the force in the hole was represented as existing only on either of the two sides of the hole. During these tasks, it required a minimal amount of information in order to determine the position of the forces. As was discussed in section 9.1.1, the experiments on object contact force input zero bits of information to the human operator regarding the direction of the force. The peg-in-hole experiments with the two sided hole provided the human operator with one bit of input information regarding the force direction.

Therefore, for the two sided peg-in-hole task, both of the sensory substitution presentations of force position information were simple. Although they accurately presented the position of the force to the test subjects, they did not distract the subjects' attention when presented simultaneously with clear visual feedback. A diagram of the manual control system for clear visual feedback and simple sensory substitution presentations of force position, showing that sensory substitution information was not needed and did not affect performance is shown in figure 94.

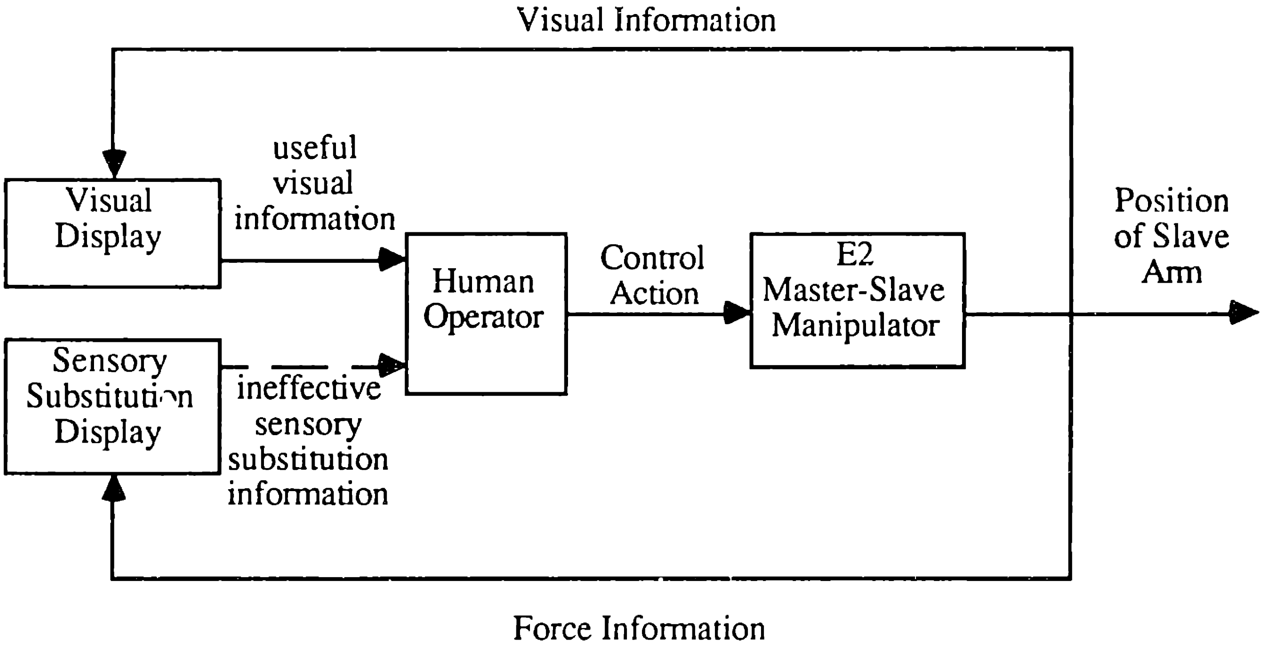

Figure 94 - Manual Control System for Clear Visual Feedback and Simple Sensory Substitution Force Information Presentations

For the results summarized in Chapter 8, figure 76, performance with an unobstructed, i.e. clear, view during the two sided peg-in-hole task, there were no significant performance differences between any of the feedback conditions. Visual feedback alone appeared to dominate the sensory feedback to the test subjects and was sufficient by itself to allow the subjects to perform the task as quickly as possible, since adding any type of force information to the visual feedback did not have an impact on performance.

Analyzing the models of bisensory information processing described in section 2.5.1 can help interpret these results. The bisensory models stated that the human operator will often pay attention to sensory information from one channel and attenuate the signal from the others when receiving stimuli from multiple sensory modalities [Oatman, 1976]. This can help to explain why additional sensory feedback did not affect performance for this task. Since the two sided peg-in-hole task was a relatively simple task, the clear visual feedback provided sufficient information to apparently maximize the operator performance for the task, and additional information was not needed. In addition, the force presentations were also simple. Therefore the force information from the additional senses did not distract or overload the operator, and did not degrade performance.

The theory of sensory dominance, discussed in section 2.5.3 also provides some insights. The sensory dominance studies found that when visual information was presented in combination with auditory or tactile information, and the information from each modality pertained to the same task, test subjects would tend to rely on the visual information, and at times even ignore the information coming from the other modalities [Posner, Nissen, and Klein, 1976]. The results found for the two sided hole peg-in-hole tasks are in agreement with the theory of visual dominance. Vision appears to have dominated the operator's attention and the addition of more sensory information made no significant difference in performance. It is important to note however, that the high quality of the visual signal, and the clear, unobstructed view of the task board allowed the subjects to depend on visual feedback in order to complete the task. When the visual feedback was of poor quality, or when the view was obstructed, much different results were obtained, as has been discussed in previous sections of this chapter.

9.6.2 Complex Sensory Substitution Presentations of Force Information

Unlike the simple sensory substitution presentations analyzed in section 9.6.1, more complex presentations were found to impede operator performance. To better explain these results, the analysis presented in this section was performed.

Complex sensory substitution presentations of force information were defined as those which represented forces that could consist of more than one component. These presentations existed during the peg-in-hole experiments with the four sided hole. In section 9.1.3 it was explained that three bits of information was presented to the operator as input information for this task. However, the amount of input information was different than the amount of information that was actually transmitted by each display to the human operator. The amount of transmitted information was equal to the amount of response information minus the amount of noise generated during transmission (see Chapter 4 for details). The displays did not perfectly transmit the force direction information to the operator since, as was shown in the psychophysical tests described in Chapter 6, mistakes were made when interpreting the force position. During the peg-in-hole experiments with the four sided hole, the auditory display distracted the subjects and hurt performance whereas the vibrotactile display did not. Therefore the psychophysical data was re-examined to determine the possible information transmission rates with each display. This could help future researchers in estimating the level at which transmitted information could become distracting and possibly overload the human operator.

In chapter 6 it was shown through the psychophysical experiments on force position that the auditory display more accurately represented force position information to the operator than the vibrotactile display. Analyzing these psychophysical results with information theory, the sixteen force directions that were presented as stimuli were divided into the eight possible force positions: left, right, top, bottom, left and top, left and bottom, right and top, and right and bottom. The results for the amount of transmitted information through each display to the test subjects are shown in table 21. For a detailed explanation of how the numbers in table 21 were calculated, and for definitions of the information theory terms used in table 21, the reader is referred to chapter 4, section 4.1.1 of this thesis.

Display	Input Information	Response Information	Noise Generated	Transmitted Information
Vibrotactile	3.0 bits	2.93 bits	1.01 bits	1.92 bits
Auditory	3.0 bits	2.88 bits	0.5 bits	2.38 bits

Table 21 - Information Transmitted for the Peg-In-Hole Test with the Four Sided Hole (Taken from psychophysical experiments for the four sided hole tasks, section 6.2.1)

Table 21 shows that the auditory display transmitted more information about the direction of the force applied by the peg inside the hole than did the vibrotactile display. This extra information from the auditory display provided the subjects with a more complex representation of the force direction.

The peg-in-hole tasks with an unobstructed view led to favorable visual conditions without time delay. In the two sided hole case, sensory substitution provided simple representations of force position that did not affect performance. However with the four sided hole, sensory substitution provided more complex information than the two sided case and the auditory display actually distracted the operator and degraded performance. Therefore the effectiveness of sensory substitution was not only a function of the quality and clarity of visual information, but was also a function of the complexity of the force presentation through sensory substitution. Future researchers and designers can use the information transmission rate of the auditory display as a guideline for future applications when additional sensory information is used to supplement vision. It is an information guideline which can help predict performance degradation due to information overload with clear visual conditions and with task conditions similar to those tested in this study.

A manual control model for complex sensory substitution presentations in the presence of clear visual feedback is shown in figure 95, showing how sensory substitution can act as a distraction to the human operator.

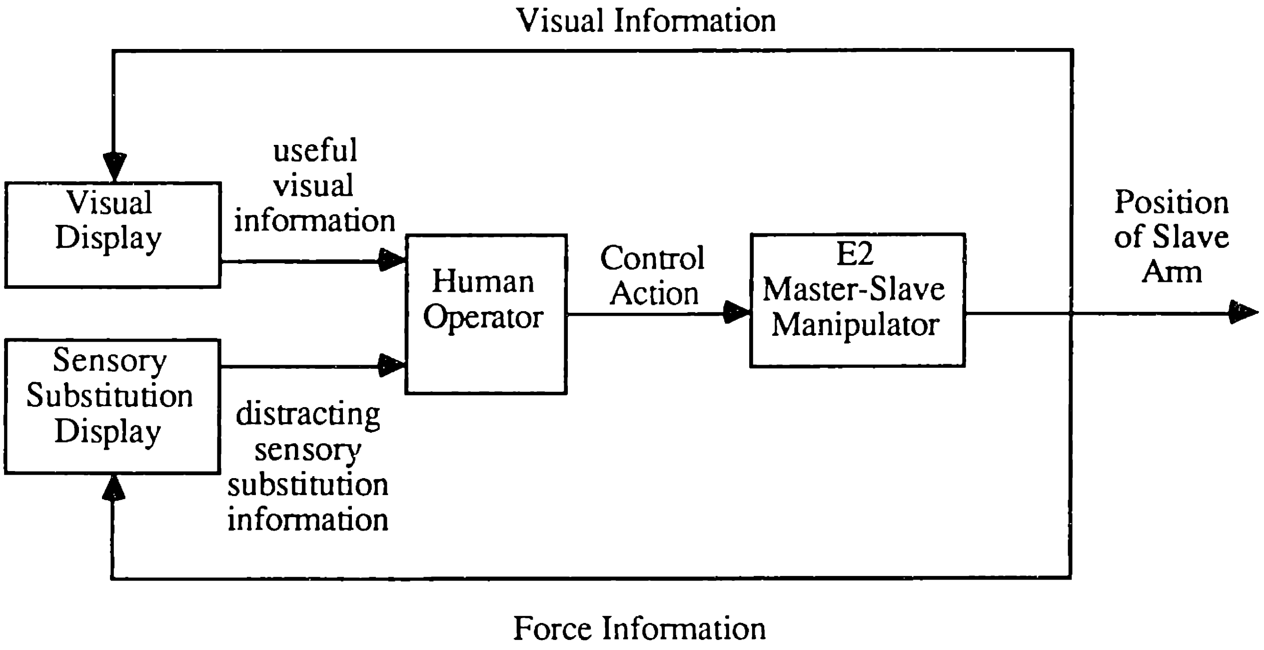

Figure 95 - Manual Control System for Clear Visual Feedback and Complex Sensory Substitution Force Information Presentations

Theories on bisensory information processing have predicted that interference among simultaneously presented auditory-visual stimuli may occur when the information is presented in a format requiring a high cognitive difficulty or at a rate of presentation such that successful alternation of attention between channels is not possible [Hartman, 1961]. In addition, if one of the displays divides the attention of the operator by too large amount, interference has been observed in previous studies which jeopardized task success [Adams and Chambers, 1962]. In this thesis, the addition of the complex auditory feedback apparently distracted or overburdened the operator, and as the bisensory information models would predict, degraded performance.

10. ANALYSIS OF REPLACING TRADITIONAL FORCE FEEDBACK WITH SENSORY SUBSTITUTION

This chapter analyzes the effects of replacing traditional force feedback with sensory substitution of force feedback. Chapters 5 through 8 noted the performance differences between traditional force feedback and sensory substitution, but did not offer any theories or detailed explanations. This chapter looks deeper into these results and proposes explanations for them. Guidelines are provided for predicting the potential benefits or disadvantages of using sensory substitution instead of traditional force feedback.

Replacing traditional force feedback with sensory substitution of force feedback was found to improve, degrade, or have no effect on performance during the experiments. Analysis of these results in this chapter is based on the following two characteristics: 1) the force detection threshold of stimulation with the sensory substitution displays was lower than the detection threshold for traditional force feedback, and 2) traditional force feedback caused the human operator's arm and hand to react to the presentation of force information whereas sensory substitution did not, but instead provided non-reactive presentations of force information.

In addition, the performance differences between replacing traditional force feedback with auditory sensory substitution versus replacing traditional force feedback with vibrotactile sensory substitution are also analyzed. The explanation proposed for these performance differences is based upon the reaction time of the test subjects with each display, and the quality of the force information presented to the test subjects through each display.

Analysis of replacing traditional force feedback with sensory substitution for representing basic force information during the object contact experiments is discussed in section 10.1. An additional psychophysical experiment on force detection threshold was performed to help analyze these results, and these experiments are also discussed in section 10.1. Traditional force feedback versus sensory substitution results for the common manipulation task experiments are analyzed in section 10.2. Section 10.2 also contains the results of another additional psychophysical experiment that examined a human's ability to interpret force position information with traditional force feedback. Comparative effects of using auditory or vibrotactile sensory substitution are analyzed in section 10.3. Degraded performance due to the simultaneous presentation of clear visual feedback with either traditional force feedback or sensory substitution with the auditory display is analyzed in section 10.4.

10.1 Analysis of Replacing Traditional Force Feedback with Sensory Substitution to Detect and Measure Object Contact Forces

This section analyzes the performance differences associated with replacing traditional force feedback with sensory substitution, for the experiments which measured basic force information (i.e. the object contact experiments). Explanations are provided for cases in which sensory substitution was superior to traditional force feedback, and for cases in which there were no significant differences between the two.

The analysis of the subset of object contact experiments which were dependent on reaction time, is primarily based on sensory substitution having a lower detection threshold for force than traditional force feedback (sections 10.1.1 to 10.1.3). For the experiments which were not heavily dependent on reaction time, but were more dependent on interpreting the magnitude of the applied force, the analysis is based on the characteristic of traditional force feedback that caused the operator's hand and arm to react to the force presentations (section 10.14).

During the experiments on presence of object contact force and the higher force range tests of the experiments on magnitude of object contact force (experiments that were heavily dependent on reaction time), both of the sensory substitution displays provided superior performance when compared to using traditional force feedback. However, for the experiments on sustained object contact force and the lower force range tests of the experiments on magnitude of object contact force (experiments that were heavily dependent on interpreting the magnitude of the applied force), there were no significant performance differences between traditional force feedback and either of the sensory substitution displays.

10.1.1 Detection Threshold for Traditional Force Feedback

The experiments on presence of object contact force were tapping tasks in which the performance objective was to make as many successful taps as possible within 15 seconds. The results were closely linked with reaction time, since the subjects were required to recognize a stimulus and then react as quickly as possible. Therefore recognizing the presence of a contact force and reacting appropriately was quicker with either of the sensory substitutions than with traditional force feedback. The results for the higher force range of the experiments on magnitude of object contact force were similar to the results obtained for the experiments on presence of object contact force, since both of the sensory substitution displays provided significantly better performance results than traditional force feedback. During the experiments on presence of object contact force, the object was fixed and the force range was unlimited. Although the objects could move and record a penalty during the experiments on magnitude of object contact force, it appeared that the higher force range (0-2 lbs.) for these experiments was sufficiently high such that the operator was able to concentrate on the speed of movement, overcome the penalty assessed, and obtain similar performance to that observed in the presence of contact force experiments.

However, the differences in these reaction times between sensory substitution and traditional force feedback, were probably heavily influenced by the test subjects having different thresholds for force detection with the sensory substitution displays than they did with traditional force feedback. Therefore the hypothesis proposed for explaining why using traditional force feedback was slower in some instances than using sensory substitution, is that the force detection threshold for traditional force feedback was higher than that for sensory substitution. This hypothesis, and the lower force detection threshold of sensory substitution compared to that of traditional force feedback, will be explained in the next few paragraphs.

The minimum force detectable by a typical force sensing resistor (fsr), the force sensor used in this thesis with the sensory substitution displays and described in detail in section 3.2, was measured at approximately 0.01 pounds. When this amount of force was detected by an fsr for sensory substitution, the auditory or vibrotactile displays would be stimulated at levels of stimulation that were well above threshold. For example, during the experiments on presence of object contact force when the minimum amount (or any amount) of force was detected, the auditory or vibrotactile displays would stimulate the test subjects in on-off mode at 32 db (re: 1 micron) for the vibrotactile display and 70 db SPL for the auditory display. For the experiments on magnitude of object contact force, the minimum amount of force detected by the fsr would result in the sensory substitution displays stimulating the subjects at levels well above threshold: 7 db (re: 1 micron) for the vibrotactile display and 46 db SPL for the auditory display. These levels would increase as the magnitude of the force increased. Therefore, when using sensory substitution, the test subjects were able to perceive a minimum detectable force of 0.01 pounds.

The minimum detectable force for the test subjects when using traditional force feedback through the E2 was unknown. Although the E2's electronics may have been able to detect very small forces, the threshold value for force that a human operator could detect coming through the E2 hand controller was unknown. In a previous study, Weinstein [1968] found that the threshold for direct pressure touch, using von Frey nylon filaments that bend at a calibrated force, was approximately 100 mg (0.0002 lbs) for the fingertips, approximately 150 mg (0.0003 lbs) for the arms, and approximately 175 mg (0.0004 lbs) for the hand. Although these thresholds are smaller than the force threshold for sensory substitution (0.01 lbs.), it was not clear what the force threshold was for the operator's hand and arm when using the E2 hand controller. Therefore an additional test was performed with the E2 in an attempt to determine the minimum detectable force through traditional force feedback. The results led to a better understanding of some of the results for the teleoperated experiments.

10.1.2 Psychophysical Test for Measuring Force Detection Threshold with Traditional Force Feedback

To aid in analyzing the performance differences between sensory substitution and traditional force feedback for the object contact experiments which were heavily dependent on reaction time, an additional psychophysical experiment was conducted. The objective of the experiment was to determine the minimum detectable force for a human operator, when using the force feedback capability of the E2. If the force detection threshold was higher than the threshold when using sensory substitution, 0.01 pounds, then one would conclude that the advantage that sensory substitution had during the object contact experiments was due to its lower force detection threshold. However, if the detection threshold for traditional force feedback was lower or similar to that of sensory substitution, then some other characteristic of either sensory substitution or traditional force feedback would be responsible for the performance differences.

A spring scale was attached to the E2 hand controller in such a way that a force could be applied to the hand controller while the test subject's hand was comfortably holding it. A two alternative forced choice experimental method was used. The choices that the test subject had for each experimental trial were either: 1) a force was present, or 2) no force was present. Twenty trials were conducted at each force level tested. One test subject was examined. A force existed during ten of the trials, and no force existed during the other ten. The ordering of force and no force trials was randomized using a random number generator for each force level. The test subject closed his eyes, and the force was applied behind the test subject so that no visual cues could be obtained by the test subject during a trial. The subject was given a ready signal and then a moment later the trial would begin and last for approximately two seconds. Then the test subject would be asked to respond if a force was presented. The response was noted and then another trial would begin. After twenty trials were completed the correct response rate was calculated. Following the convention for a two alternative forced choice experiment, the force level at which a 75% correct response rate was calculated would be the threshold force level. A correct response rate above 75% would signify an above threshold value, and a correct response rate below 75% would signify a below threshold value.

The tests began at a force level which was well above threshold, 1.5 pounds, which resulted in a 100% correct response rate. The force level was then gradually decreased until a below threshold value was calculated at 0.25 pounds. The threshold force level for detection by a human operator using the E2 was determined to be approximately 0.375 pounds. Figure 96 displays the experimental results.

The threshold for force detection by the human operator with traditional force feedback, 0.375 pounds, is much higher than that with either of the sensory substitution displays, 0.01 pounds. This difference in force detection threshold for the human operator could have affected performance during the magnitude and experiments on presence of object contact force. Once the force was detected, the subjects were required to move to the next target as quickly as possible. Therefore being able to detect forces sooner would have improved performance. This probably was a major reason why performance was significantly better with the sensory substitution displays than with traditional force feedback for the two tests which were closely linked to reaction time, i.e. the experiments on presence of object contact force and the higher force range for the experiments on magnitude of object contact force.

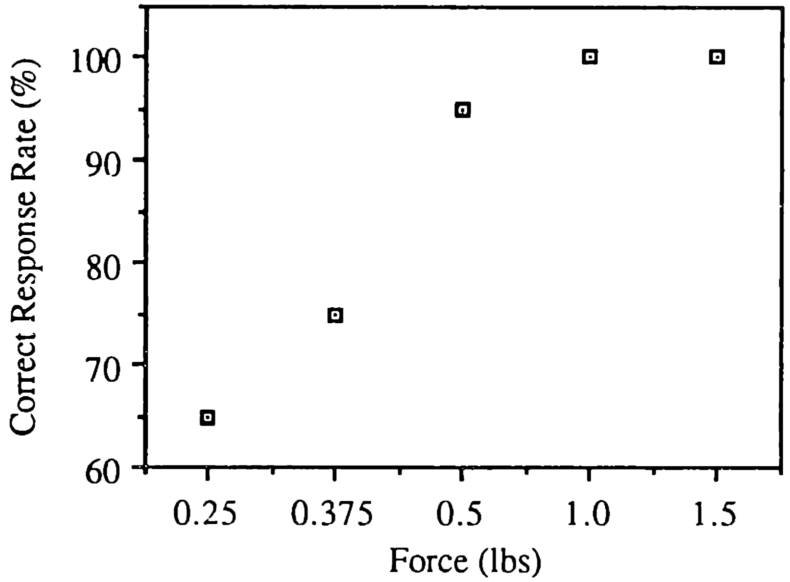

Figure 96 - Detection Threshold for Force with Traditional Force Feedback.

10.1.3 Increased Force Sensitivity through Sensory Substitution

The results of the psychophysical experiment on force detection threshold with traditional force feedback, have significance beyond their implications for the analysis of the object contact experimental results in this thesis. The lower threshold for sensory substitution could lead to future benefits for using sensory substitution instead of traditional force feedback.

The results for the force detection threshold experiment showed that sensory substitution of force feedback had an advantage over traditional force feedback: sensory substitution can permit the presentations of small forces to be perceived at high stimulation levels without affecting the motions of the human operator. Sensory substitution allows the feedback gain to be as high as desired so that the smallest force detectable by the most sensitive force sensors can be easily perceived by the operator, without any ill effects on the motions of the operator or on the stability of the system.

When traditional force feedback is used, even though the force sensor itself maybe sensitive, the operator may be limited by a high threshold for force detection through the hand controller as was shown in the previous section. To raise the sensitivity of traditional force feedback, i.e. lower its detection threshold, one could raise the feedback gain. This may be desirable for certain tasks in which detection of small forces is needed, and quick, precise, or sustained motion is not required. However, due to the nature of traditional force feedback, high feedback gain would make motion of the control arm more difficult, or perhaps even cause instabilities for some tasks. For example, with a relatively high feedback gain, a small force at a remote location would be presented as a large force to the human operator's arm and hand muscles. This would impose a large force on the operator and make the input hand controller more difficult to move. Thus the task would be made more physically difficult, the operation would be slowed down, and the rate of human operator fatigue would be increased. If the gain was too excessive, instabilities could occur. For the tapping tasks performed in this thesis, high feedback gain for traditional force feedback would have improved detection of contact force, but would have also slowed down the test subjects and made the performance much worse than it was with the normal 1:1 gain values. Sensory substitution however does not pose these problems, since the feedback gain can be made exceedingly high without affecting operator movement.

There are many applications in which increased sensitivity of force detection could be useful. For example, if a physician were performing a surgical procedure in which knowing small forces being applied to the patient were helpful, sensory substitution could be helpful. For a small force applied to the patient, an above threshold stimulus could be presented through sensory substitution. If the same technique were used with a high feedback gain for traditional force feedback, movements could be slowed or made overly difficult. High sensitivity to small forces could also be useful for a telemanipulation task involving a delicate instrument or one that requires the application of small forces for successful task completion.

There may also be situations similar to the ones described above, in which a high feedback gain for traditional force feedback might be preferable to sensory substitution of force feedback. For example, it might be desirable in some situations to slow down motion, or to impede the human operator's motions to help prevent possible damage of a delicate object. Therefore the utility of increased force sensitivity through sensory substitution or traditional force feedback would be dependent upon the goals of the task.

10.1.4 Effect of Operator Induced Movements on Object Contact Force Experiments

In addition to detection threshold being a major factor in analyzing the object contact experiments, the reactive forces applied onto the human operator by traditional force feedback also influenced the experimental results. An analysis of this characteristic and its effects on the experimental results are described in this section.

For the experiments on magnitude of object contact force, performance was measured by taking the total number of taps in fifteen seconds and then subtracting a penalty of one tap for every 0.25 inches of displacement of the target objects (see chapter 5 for details). An interesting result occurred when analyzing the penalty data for these tasks. When using traditional force feedback, there was no significant difference in the penalty assessed between the higher and lower force ranges. This was not the case for the vibrotactile or auditory displays. In other words, the penalty incurred with traditional force feedback was nearly identical irrespective of the allowable force range.

The major difference in the performance results for the experiments on magnitude of object contact force occurred when comparing the lower and higher acceptable force ranges. At the higher range, both the auditory and vibrotactile displays yielded significantly better performance than traditional force feedback. Whereas at the lower range, there were no significant differences between traditional force feedback and the auditory and vibrotactile displays. The hypothesis proposed concerning traditional force feedback is that although the subjects were not able to detect and react as quickly to the traditional force feedback cue, traditional force feedback provided an additional advantage that was particularly helpful at the lower force level. Traditional force feedback not only indicated to the subject that contact at a certain level has been made, but it also prevented the subject from moving his/her arm further and causing excessive unwanted movement before the force cue was detected through the subject's own sensory system. This was probably why the penalty assessed when using traditional force feedback was approximately constant for both force ranges.

The critical point in analyzing these results and combining these characteristics for traditional force feedback with those discussed in the previous sections, is that the operator was unaware of the existence of the force being presented even though the E2 had stopped excessive movement. Since the experiments on presence of object contact force and the higher force range of the experiments on magnitude of object contact force were largely dependent on reaction time, and since the subject had to detect the force in order to respond to it, the lower force detection threshold for sensory substitution was an advantage over traditional force feedback. However, at the lower force range for the experiments on magnitude of object contact force the task was dependent not only on reaction time, but was heavily dependent on minimizing error due to the greater ease with which penalty could be accumulated at the lower force range. Therefore the induced movement caused by traditional force feedback prevented the operator from building up excessive penalty, even though the detection of the force was below threshold.

The same theory can be applied to the experiments on sustained object contact force. The sustained object contact task was not heavily dependent on reaction time, but was dependent on maintaining a force within specified limits for three seconds four times consecutively (see chapter 5 for details). Successful sustained contact for three seconds was indicated to the test subjects by a contact light. Therefore, although the detection of the contact was harder for the subjects with traditional force feedback, this did not have a large effect on performance since the contact light indicated when three seconds had elapsed. If the experiment had been conducted differently, and the subjects had to judge for themselves when three seconds had elapsed without the aid of a contact light, the results might have shown better performance for sensory substitution. In that case the subjects would have been able to detect contact quicker, and be certain of the three seconds of sustained contact sooner with sensory substitution than would have been possible with traditional force feedback.

Therefore the advantage that the auditory and vibrotactile displays had over traditional force feedback, in the presence of contact force experiments and in the magnitude of contact force experiments at the higher force range, was no longer substantial. It was lost to the added advantage of forces being applied to the subject's hand and arm that existed with traditional force feedback, during the lower force range tests of the magnitude of contact force experiments and during the sustained contact force experiments.

10.2 Analysis of Replacing Traditional Force Feedback with Sensory Substitution for Common Manipulation Tasks

The analysis in these sections is mainly founded on the premise that traditional force feedback moved the test subjects' arms and hands to desirable positions, due to its force reflective nature. The common manipulation (i.e. peg-in-hole) experiments had slightly different results than the object contact experiments. With a time delay, sensory substitution was clearly better than traditional force feedback because sensory substitution did not produce instabilities and improved performance. However, without a time delay, sensory substitution did not pose any advantages over traditional force feedback as it did during some of the object contact experiments. Further, traditional force feedback was significantly better than sensory substitution when the view was obstructed. Additional analyses were therefore conducted to examine the results of the peg-in-hole experiments, and are presented in the following sections.

10.2.1 Using Sensory Substitution Without Instabilities in the Presence of a Time Delay

The effects of presenting force information in the presence of a time delay were discussed in Chapter 7. Traditional force feedback causes operator induced movements, and in the presence of a time delay these movements become delayed inputs into the system. After this process repeats itself, instability quickly occurs. Therefore the reactive nature of traditional force feedback discourages its use when operating with a transmission time delay.

Sensory substitution, on the other hand, was capable of presenting force information without causing operator induced movements. As a result, sensory substitution did not cause any instabilities when presented with a time delay. Further, sensory substitution even improved performance in the presence of a time delay as was discussed in Chapter 9.

10.2.2 Replacing Traditional Force Feedback with Sensory Substitution for Obstructed Views

Substituting traditional force feedback with sensory substitution when the view was obstructed led to degraded performance for both the two sided and four sided peg-in-hole tasks. The advantage that traditional force feedback had over sensory substitution for these tasks can probably be attributed to its not only providing a cue to the operator concerning force information, but also forcing the subjects' hands to proper positions. This made insertion significantly quicker with traditional force feedback than with sensory substitution of force feedback, which provided only force cues.

However, it was also hypothesized that the performance differences could have been caused by traditional force feedback presenting the position of a force to the human operator with more clarity than sensory substitution. Therefore an additional psychophysical experiment was needed to test this hypothesis.

10.2.3 Psychophysical Test for Measuring the Capability of Traditional Force Feedback to Present Force Direction Information

It was not perfectly clear why traditional force feedback displayed advantages over sensory substitution during obstructed view performance. Amongst the characteristics of traditional force feedback that could explain the results are: 1) the force reflective nature of traditional force feedback, and 2) an increased ability to interpret force direction with traditional force feedback. Another psychophysical experiment was conducted to examine the second characteristic further.

This new psychophysical test measured the ability of a test subject to interpret the position of a force through traditional force feedback. These results were then compared to the results obtained with the sensory substitution displays through the similar psychophysical test discussed in Chapter 6. In Chapter 6, it was noted that the psychophysical tests for interpreting the direction of a force using the auditory and vibrotactile displays were conducted, in part, to help predict the performance results with an obstructed view. However, traditional force feedback was not tested as part of this psychophysical test. Thus to obtain a general idea of how well sensory substitution compared to traditional force feedback for presenting the direction of a force to the human operator, the psychophysical test was repeated with traditional force feedback.

If traditional force feedback were to improve the human operator's ability to interpret the direction of a force compared to sensory substitution, then this would indicate that this improved ability probably contributed to traditional force feedback producing better performance during the obstructed view peg-in-hole tasks. If, however, the interpretation of force position information was similar or worse than that with sensory substitution, then the force reflective nature of traditional force feedback would most probably explain why performance with traditional force feedback was significantly better than with sensory substitution during the manipulation tasks with an obstructed view.

A spring scale was attached to the the end of the E2 hand controller. During a trial the spring scale would be pulled for approximately two seconds with a four pound force, in one of the sixteen possible directions used in the psychophysical tests outlined in section 6.2.1. Each of the positions was tested a total of five times for a total of eighty experimental trials. The ordering of the presentations was randomized with a random number generator. One subject was tested, and was required to hold the hand controller in a fixed position while the force was being applied, to ensure that he was interpreting properly the direction of the force. After each trial, the test subject responded as to which position was presented. Training was conducted, and breaks were given every twenty trials to alleviate the effects of fatigue on the hand muscles. A barrier was placed between the test subject's hand and the spring scale so that the test subject would not receive any visual cues regarding the direction of the force.

The results for this psychophysical test with traditional force feedback were evaluated with the same four criteria used to evaluate the psychophysical test results with sensory substitution (see section 6.2.1): 1) exact force position, 2) force quadrant, and 3) dominant force. The results are shown in table 21.

Criterion	Correct Response Rate
Exact Force Position	65%
Force Quadrant	100%
Dominant Force	100%

Table 21 - Results for Psychophysical Tests on Force Direction with Traditional Force Feedback

The results shown in table 21 are similar to those presented for the sensory substitution displays in chapter 6. Although a rigorous statistical analysis was not possible due the differences in number of subjects, one can see similarities especially between traditional force feedback and the auditory display which had a 66.9% correct response rate for exact force position, a 96.3% correct response rate for force quadrant, and a 98.8% correct response rate for dominant force. The results for the vibrotactile display presented in Chapter 6 were a 45.7% correct response rate for exact force position, an 84.1% correct response rate for force quadrant, and a 97.5% correct response rate for dominant force. Taking into account the analysis conducted in Chapter 6 on these psychophysical measures, it is reasonable to conclude that the auditory display represented the position of the forces approximately as well as traditional force feedback.

Thus the advantage provided by traditional force feedback can probably be attributed to the fact that force feedback not only provided a cue to the operator concerning force information, but also guided the subjects' hands. For this reason, therefore, traditional force feedback made insertion quicker than with sensory substitution. As was the case with some of the experiments analyzed previously, this was a scenario in which the forces on the subjects' hands helped performance.

However, most important was the demonstration that sensory substitution enabled the task to be completed successfully without any useful visual feedback, and with the operator relying entirely on one of the sensory substitution displays. For this type of task, therefore, if traditional force feedback were not available, and if vision became degraded or obstructed for short or long periods of time, the task could still be successfully completed by using sensory substitution.

10.3 Analysis of Replacing Traditional Force Feedback with the Auditory Display versus with the Vibrotactile Display

For some of the experiments, there were performance differences between using the two sensory substitution displays. This section presents analyses that propose explanations for these differences between the vibrotactile and auditory sensory substitution displays.

The performance differences between using the auditory display and using the vibrotactile display can best be explained by examining two differences when using the displays: 1) differences in human operator reaction time to each of the displays for these particular tasks, and 2) differences in the complexity of the force presentations through each of the displays. These characteristics are explained in more detail in the following sections.

10.3.1 Vibrotactile and Auditory Displays for Representing Object Contact Forces

The results for the presence of contact force experiments showed that the auditory display provided significantly better performance than the vibrotactile display. As was explained earlier, the results for these experiments were probably closely linked with reaction time, since the subject was required to recognize a stimulus and react as quickly as possible. Recognizing the presence of a contact force and reacting appropriately was quicker with the auditory display than with the vibrotactile display.

However, the literature does not contain any apparent evidence of significant differences in general reaction times between the auditory and tactile modalities [Welch and Warren, 1986]. Therefore, the differences in reaction time between the auditory and vibrotactile displays that were found, are somewhat unique to this thesis. These differences in reaction times must have, therefore, been due to some aspect of the design of the displays used in this thesis, or to the nature of the task performed.

The other significant difference between the auditory and vibrotactile displays during the object contact force experiments was discovered when examining the results for the higher force range for the magnitude of contact force tests. The results were similar to the results obtained for the presence of contact when the object was fixed and the force range was unlimited. It appears that the higher force range was sufficiently high that the operator was able to concentrate on the speed of movement, overcome the penalty assessed, and obtain similar performance to that observed in the presence of contact force experiments. These results, like those for the experiments on presence of contact force, were probably most closely linked with reaction time, and the auditory display had significantly better performance than the vibrotactile display for these particular experiments.

As was discussed in section 10.1.1, the sensory substitution displays provided a lower detection threshold for force than traditional force feedback. This contributed to the superiority of sensory substitution for these tasks. However, no such differences existed between the vibrotactile and auditory displays. The minimum detectable force by a typical force sensing resistor (fsr) was approximately 0.01 pounds. When the minimum amount of force was detected the auditory or vibrotactile displays would stimulate the test subjects at above threshold levels, 7 db (re 1 micron) for the vibrotactile display and 46 db SPL for the auditory display. These two minimum stimulus levels were calculated as being of equal sensation magnitude by applying the Stevens [1959] method for determining equal sensation magnitude across modalities. Therefore the differences between the auditory and vibrotactile displays were probably most closely linked to pure reaction time, with the subjects' reaction time being quicker with the auditory display for the experiments on presence of object contact force. However, as was discussed earlier, these differences in reaction times between the vibrotactile and auditory displays are not supported by the literature. Therefore, the reaction time differences observed between the auditory and vibrotactile displays were probably due to some design aspect of the displays, or to the nature of the task tested.

10.3.2 Auditory and Vibrotactile Displays with Obstructed Views

Applying the results obtained in the psychophysical experiments could help to explain relative performance differences for the vibrotactile and auditory displays with obstructed views. Test subjects commented that when inserting the peg into the hole without a time delay, what seemed to be important was just getting a general idea of the direction of the force and the side of the hole being contacted with the largest amount of force, and not the exact position of the force vector. During the obstructed view tasks performed without a time delay, the tasks were easy enough so that only a rough estimate of force location was needed. Additional information about the exact force position was not necessary. For the dominant force criterion, each of the sensory substitution displays performed similarly well and with very high correct response rates, which suggested that the auditory and vibrotactile displays would produce similar results for these tasks.

Therefore, the dominant force criterion of the psychophysical tests correctly predicted the results for the obstructed view experiments with the four sided hole.

When conducting the obstructed view manipulation tasks with a time delay, performance using the vibrotactile or the auditory displays was not significantly different from each other for the two sided hole tests. However, for performing the obstructed view scenario with the four sided hole and a time delay, the results were different from those obtained with the two sided hole obstructed view experiments with a time delay. In the latter case there was also a significant difference in mean task time between using the vibrotactile or auditory displays, with the auditory display producing significantly better performance.

Examining the psychophysical experimental results for the four sided peg-in-hole task discussed in section 6.2.1, can provide some possible insights into these results. The psychophysical test criteria one and two (exact force position and force quadrant) were more difficult criteria for the subject to respond to correctly, since they required more understanding of the actual force position and not just an estimate of the general location of the force. For these criteria, the auditory display produced significantly higher correct response rates than did the vibrotactile display. These psychophysical results correlate to the results of the four sided peg-in-hole obstructed view experiments with a time delay, since the auditory display had significantly better performance than the vibrotactile display.

With a time delay, subjects commented that the more information they could get the better off they were when performing the tasks. The presence of a time delay with an obstructed view made it more difficult for subjects to interpret the position of a force (i.e. the position of the peg). Therefore, any additional information about the position of the peg that either of the two sensory substitution displays could provide was useful. The auditory display provided more information about position than did the vibrotactile display, as was indicated by the psychophysical experiments. This increased quality of information between the two sensory substitution displays previously appeared to be either a hindrance (clear view without time delay), or of no significance (obstructed view without time delay, clear view with time delay). But with an obstructed view and a time delay, more precise position information was helpful and the auditory display provided significantly better performance than the vibrotactile display. In this way, the psychophysical experiments correctly predicted performance for the actual peg-in-hole tasks.

The major result from these tests was the demonstration that it was possible to perform these tasks with a time delay and without any useful visual information. These tasks would be impossible under conventional means since neither visual feedback or traditional force feedback could help the operator perform the task. Thus sensory substitution made it possible to successfully complete tasks that would normally be impossible to perform.

10.4 Performance for Manipulation Tasks with Clear Views

Perhaps the most surprising results in this thesis were the cases in which traditional force feedback and sensory substitution with the auditory display, impeded operator performance. This occurred during the common manipulation experiments with a clear view. This section explores the reasons behind these unexpected results, and offers theories to explain them.

When performing the manipulation task with a two sided hole, neither of the sensory substitution displays nor traditional force feedback had any effect on performance compared to performing the task with visual feedback alone. However, for the four sided peg-in-hole task, sensory substitution with the auditory display and traditional force feedback led to degraded performance when compared to using direct vision alone, whereas sensory substitution with the vibrotactile display did not.

In the case of traditional force feedback, it seemed as though the subjects were constrained from executing their desired motions. Earlier it was discussed that force feedback not only presented force cues, but it also forced the hand and arm of the operator into certain positions. This can be useful in some instances as was noted in the examples cited in sections 10.1.4 and 10.2.2, but for a tight fitting and constrained task like the four sided hole peg-in-hole task, force feedback impeded the arm from going where the subject desired. Visual feedback was very clear and gave the subject a clear indication of the desired movement. However force feedback significantly increased the task times by constraining this movement.

In the case of auditory sensory substitution, it appeared as though the subjects experienced information overload. The psychophysical experiments described in section 6.2.1 indicated that the auditory display gave much more information to the operator than the vibrotactile regarding the exact position of the forces. This high resolution auditory information may have been too much for the operator to handle when combined with the clear visual feedback. Since vision was apparently the best channel for indicating position for this task, the addition of the auditory feedback overloaded the operator with information and decreased performance.

Insights into these results can be obtained by reviewing the models of bisensory information processing discussed earlier in section 2.5. Hartman [1961] found that interference between the auditory and visual modalities occurred when the information was presented in a format requiring a high cognitive difficulty or at a rate of presentation such that successful alternation between the senses was not possible. This was apparently not the case for the peg-in-hole experiments with the two sided hole since the force representations were fairly simple when presented auditorally. However for the peg-in-hole experiments with the four sided hole, the auditory force presentations became more complex as did the task itself. This complexity of presentation through the auditory channel apparently distracted or overburdened the operator, and as the bisensory information models would predict, degraded performance.

11. CONCLUSIONS, RECOMMENDATIONS, & FUTURE RESEARCH

The first part of this chapter draws conclusions and makes recommendations based on the experimental results presented in this thesis. Recommendations for future research work are presented in the second part of this chapter.

11.1 Conclusions and Recommendations.

Throughout the many experiments that were conducted during this thesis research, the feasibility of sensory substitution for force feedback through the vibrotactile and auditory displays was demonstrated. Sensory substitution was successfully used in this thesis to display the presence and magnitude of instantaneous and sustained object contact forces, and to display the direction of a force for common manipulation tasks. Therefore sensory substitution can be considered as a proven method by which force information can be presented if traditional force feedback is too costly, impractical, inefficient, or unstable for the given task conditions.

11.1.1 Teleoperation with a Time Delay

The experiments that were conducted with a time delay, demonstrated that sensory substitution provides a solution to the instability problem that occurs when force feedback is traditionally used in the presence of a time delay. Due to traditional force feedback presenting force information to the operator by applying forces the operator's hand and arm, operator induced instabilities can occur if teleoperation is performed in the presence of even small time delays. Since the sensory substitution displays tested in this thesis do not induce operator movements, these displays presented force information to the test subjects without causing instabilities. The time delay experiments demonstrated that force information could be now be presented successfully through sensory substitution in the presence of a time delay, without the instabilities that would normally occur with traditional force feedback.

In addition, operator performance was improved when using sensory substitution in the presence of a time delay for the manipulation tasks tested, even when high quality visual feedback was available. Further, with an obstructed view and time delay, the peg-in-hole tasks could still be completed by relying solely on either of the sensory substitution displays.

Therefore if time delayed teleoperation is necessary, sensory substitution for force feedback can be used without instabilities. Further, performance improvements can be expected for many manipulation tasks due to the enhanced abilities to perceive critical force magnitudes, and to manipulate objects with force direction information through sensory substitution displays.

11.1.2 Performing Tasks Without Useful Visual Feedback and Without Traditional Force Feedback

One of the experimental conditions for the peg-in-hole tasks was to perform the tasks with fully obstructed visual views. Under these conditions, the tasks were impossible to perform when relying only on visual feedback. In addition, when sensory substitution was tested, the tasks with an obstructed view were conducted without traditional force feedback. The sensory substitution presentations of the forces acting at the remote worksite worked enabled the operators to perform tasks while being totally dependent on sensory substitution for feedback. This was demonstrated both with and without the presence of a time delay.

Performing the tasks with an obstructed view in the presence of a time delay posed a situation where relying on visual feedback would make the task virtually impossible, and using traditional force feedback was not possible due to the presence of a time delay. Therefore the only way to complete these tasks was to rely completely on the sensory substitution displays, and the tasks were completed successfully with either the vibrotactile or auditory displays. Thus sensory substitution enabled tasks that would normally be impossible to perform using conventional methods even if vision and traditional force feedback were available, to be successfully completed.

Therefore if a teleoperation scenario were to arise in which the visual feedback became degraded to the point that it no longer conveyed useful information to the human operator, and if traditional force feedback were not available or would lead to instabilities, many remote manipulation tasks could still be performed with the human operators relying on sensory substitution as the primary mode of feedback.

11.1.3 Degraded Visual Conditions

Sensory substitution added to visual feedback was found to be particularly useful when the visual feedback was poor or delayed. Sensory substitution improved performance during the following scenarios: 1) the experiments on object contact forces for which the perception of depth was important but difficult through visual feedback alone; 2) the peg-in-hole tasks when the view was obstructed; 3) the post-hoc experiments in which the view was partially obstructed or degraded through low visual resolution. In addition, as was described in section 11.1.1, sensory substitution also improved performance in the presence of a time delay.

In future teleoperation applications if poor visual conditions are present, the addition of sensory substitution for force feedback can be used to compensate for some of the performance degradation due to poor vision or time delay.

11.1.4 Comparisons to Traditional Force Feedback

For representing basic force information during the experiments on object contact forces, sensory substitution provided performance levels that were as good, or in some cases superior to, those obtained with traditional force feedback when detecting the presence and magnitude of instantaneous and sustained contact forces. The advantage that sensory substitution had over traditional force feedback was observed for tasks highly dependent on reaction time to the force stimulus. The sensory substitution displays had a much lower detection threshold for force than traditional force feedback. This was primarily due to the ability to increase the feedback gain with sensory substitution which enabled a small force to be presented as a stimulus of large magnitude. If the same approach were taken with traditional force feedback and the feedback gain were increased, movement of the manipulator would become slowed and more difficult and instabilities could occur.

For tasks during which increased force sensitivity and early force detection were important, for example manipulation tasks in which the detection and application of light forces were critical, sensory substitution of force feedback could improve the human operator's ability to detect and interpret those small forces without impeding movement or risking instability. On the other hand, for tasks during which it may be desirable to detect small forces and oppose the operator's input into the system, traditional force feedback with a gain that is high enough to improve detection but also low enough to ensure stability may be more attractive.

During the tasks which were highly dependent upon the perception of the magnitude of a force or on tracking the changes in the magnitude of a sustained force, performance with sensory substitution was as good as performance with traditional force feedback. Thus for tasks involving the application of a one dimensional force of a specific magnitude either instantaneously or over a period of time, sensory substitution could provide force perception similar to that obtained with traditional force feedback.

Traditional force feedback did however have significantly shorter mean task times when compared to sensory substitution of force feedback for the common manipulation tasks when the view was obstructed. The advantage of traditional force feedback for these tasks was probably that force feedback not only provided a cue to the operator concerning force information, but also guided the subjects' hand and arm motions and helped direct the peg into the hole by exerting forces onto the subjects' arms and hands. This made insertion quicker with traditional force feedback than with sensory substitution of force feedback, which provided only force cues. If a time delay does not exist, and if an insertion task or a manipulation task in which the end effector needs to be positioned based on force information, traditional force feedback could be superior to sensory substitution because it can help guide the operator's inputs to the correct positions.

As was mentioned in section 11.1.1, perhaps the biggest advantage of using sensory substitution of force feedback instead of traditional force feedback, is the ability to use sensory substitution in the presence of a time delay.

11.1.5 Complexity of Information Transmitted

The psychophysical tests for interpreting force direction (section 6.2.1) determined that the auditory display was more accurate in presenting the exact direction of a force from the success rates of identifying force position. Further, using information theory, the amount of transmitted information from the displays to the human operator about the force direction was greater with the auditory display.

This greater amount of transmitted information was found to be both an advantage and a disadvantage when compared to the vibrotactile display. Greater transmitted information was an advantage during the four sided peg-in-hole obstructed view experiments with a time delay, in which the auditory display had significantly better performance than the vibrotactile display. During this experimental condition, the subjects were in need of as much information as possible. However, when the view was unobstructed and no time delay existed, performing the four sided peg-in-hole task with the auditory display created a performance decrement compared to using vision alone. The vibrotactile display did not have this adverse effect for those conditions. Therefore the larger amount of transmitted information through the auditory display was a hindrance when the subjects had sufficient information through visual feedback and no time delay existed.

Therefore, one needs to carefully balance the amount of information coming to a human operator through multiple sensory channels. If a large amount of transmitted feedback information is possible through more than one modality, there would be a risk of overloading the human operator. However if one sensory channel is heavily degraded, then the secondary sense that provided the largest amount of information could be expected to produce better performance results.

11.1.6 Training

For all of the experimental tasks and conditions, training was straightforward and fairly quick. On average, approximately one hour of training was necessary prior to each experimental session. This was aided by the fact that the same four test subjects performed all the tasks, and therefore gained experience as they progressed through the experimental schedule. The standard procedure was to first inform the subjects about the nature of the task and the objectives by which their performance would be measured. Then they would perform the tasks informally to attain some familiarity. Afterwards, practice trials were conducted and practice data was recorded. The practice trials would continue until the learning curves appeared to flatten and performance was stable. The number of practice trials necessary to attain this flattening of the learning curve could range anywhere from ten to one hundred, depending on the task, the feedback conditions, and the subject. A counterbalanced experimental design was used to further counteract any residual learning effects that might have occurred during the experimental trials.

The sequence in which the experimental tasks were conducted also facilitated learning. The first experiments conducted were the psychophysical experiments on absolute judgements and just noticeable differences. These psychophysical experiments gave the subjects the opportunity to become familiar with the sensory substitution displays, and how the different vibrotactile and auditory stimuli would be presented. These were followed by the object contact tasks. These were the simplest teleoperator experiments conducted, and gave the subjects an opportunity to become familiar with using the E2 manipulator, and to coordinate their motor actions with the different types of feedback they received. The peg-in-hole tasks were next: two sided with a clear view, followed by two sided with an obstructed view. Time delay experiments for the two sided peg-in-hole with a clear view were then conducted, and they were followed with the two sided obstructed view time delay tests. The four sided hole psychophysical experiments were then conducted, and gave the subjects the opportunity to become proficient in recognizing the force positions indicated by the displays. Afterwards the four sided peg-in-hole experiments were conducted in the following order of increasing difficulty: clear view, obstructed view, clear view with a time delay, obstructed view with a time delay.

Therefore the subjects gradually moved from an easier task to a more difficult task throughout the running of the experiments, which spanned approximately seven months. This schedule, along with the training sessions that took place throughout the testing, enabled the subjects to become experts on performing each experiment in an efficient manner.

During future applications, task planners should take note that appropriate and sufficient training has taken place in order for sensory substitution to be most useful. Without proper training, performance can be expected to be significantly worse than what would have occurred if training had been conducted.

11.1.7 Additional Benefits of Using Sensory Substitution for Force Feedback

Being able to use sensory substitution to perform tasks with poor visual feedback and without traditional force feedback could provide significant cost advantages in many teleoperation scenarios. For example, sensory substitution could reduce the requirement for high quality visual displays since some tasks might be able to be performed by relying on sensory substitution. Perhaps lower quality visual feedback in combination with sensory substitution would suffice, even if visual feedback were not entirely eliminated. This reduction in the need for high quality visual feedback would lead to cost savings. In addition, a reduction in the need for expensive force reflecting systems by utilizing sensory substitution might also be cost effective.

Sensory substitution may also be a valuable back-up plan for many tasks. Even if high quality visual feedback were available and sufficient enough so as to maximize operator performance, sensory substitution could be used as a contingency plan if the visual signal were to fail momentarily or if the view were to become obstructed for some reason. This would be particularly advantageous if traditional force feedback were not available due to design considerations, cost considerations, or the presence of a time delay.

11.2 Future Research

The following sections discuss research areas in which the research conducted in this thesis could be continued or expanded.

11.2.1 Improved Display Designs

One thrust of future research could be directed towards improving the design of the sensory substitution displays. For example, perhaps an auditory display that would provide more resolution for localization, such as 180 degree localization, would be useful for certain tasks when the positions of the forces could vary more than they did in these experiments. The auditory display used in this thesis could only change localization cues by varying relative loudness differences between the two ears. Therefore, the positions of the tones could only vary along a straight line between the two ears. The auditory display was also somewhat limited due to its having only 4 bits for loudness control. An auditory display with the ability to present more levels of loudness may or may not improve the accuracy to perceive force magnitude.

Additional research on the design of vibrotactile displays could also be worthwhile. The vibrotactile displays were all located on the fingertips and palm of the hand. These locations served two purposes: first, they were the skin locations that were most sensitive to vibration, and second, they were positions that corresponded well to the positions of the forces that were expressed by the manipulator onto the remote task environment. Perhaps different skin locations would be more appropriate for other tasks. For example if a task involved the use of forces whose positions would vary greatly from those examined in this thesis, different locations on the skin might produce better results. A study which would examine the correlation between the skin location of the vibration and the human operator's ability to accurately determine the location and magnitude of the force in the remote environment, could improve the designs of future vibrotactile displays.

11.2.2 Additional Visual Parameters

Visual parameters which were not tested during the teleoperated tests may also affect the usefulness of sensory substitution. These parameters include frame rate, resolution, grayscale, subtended visual angle and the camera viewpoint. Future work that would test these conditions would be helpful in strengthening or weakening the hypothesis that the value of sensory substitution for telemanipulation is dependent on the quality of the visual feedback. In addition, investigating the effects of sensory substitution on various levels of degradation of vision would also be worthwhile. This could help determine threshold or cutoff levels of degradation beyond which sensory substitution would help performance, and below which sensory substitution would make no significant difference in performance.

11.2.3 Psychophysical Experiments

The force position psychophysical test (section 6.2.1) was a new and unique test, and provided some valuable insights into the performance obtained with each display during the peg-in-hole teleoperated tasks. Future psychophysical experiments designed to test different aspects of sensory substitution may prove to be useful as well. These tests are probably most efficient if they correlate to some teleoperated task with sensory substitution. In that case they would not only provide perceptual data to evaluate sensory substitution, but would also help to analyze performance results for teleoperated experiments.

11.2.4 Improving the Measurement of Sensory Information

The experimental results showed that the addition of sensory substitution could improve, degrade, or have no effect on performance. This was largely dependent on the quality of the visual feedback presented to the test subjects. If visual conditions were not clear, the subjects were in need of information and sensory substitution facilitated performance. When visual feedback was clear, the subjects appeared to not need any additional information and the addition of sensory substitution had no effect or a negative effect on performance. These results therefore appeared to be in some way linked to the amount of information presented to and processed by the operator concurrently through two senses. Increasing the total amount of information presented to the operator through two senses generally increased performance up to a point beyond which additional information appeared to overload the operator, divide attention, and hurt performance.

It was possible to estimate the amount of information transmitted through the sensory substitution displays concerning force position from the psychophysical experiments on force position that were conducted. However, it was not possible to measure the total amount of information transmitted to the subjects about the task through all of the active senses (vision and sensory substitution). If a method by which the amount of information presented to the operator through different senses for various tasks could be measured, additional insights could be drawn to explain the effects of quantified amounts of sensory information on human operator performance. Future research could explore the limits of sensory information processing, and recommend proper mixes of information based on the amount of information conveyed by the displays.

11.2.5 Substitution of Information within a Sense

It may also be useful to investigate substituting information along different axes within a sense. For example, the results of the tracking experiments referenced earlier in this thesis [Massimino, 1990], showed that tracking a target in the z-direction (in and out of the monitor) was more difficult than tracking a target in the x or y-directions (horizontal and vertical). If it were possible to substitute the axes of tracking for one another, i.e. when z-direction tracking was important it could be presented to the operator as x or y-direction tracking, performance might be improved. Other ways in which certain aspects of perceiving information through one sense can be substituted by other representations within the same sense could be tested, and may provide some new ways in which information could be efficiently presented to improve teleoperator performance.

11.2.6 Expanding the Applications

Applying sensory substitution to different systems and a greater variety of tasks could also be done. Examining the effects of sensory substitution on operator performance for longer and more involved teleoperation tasks than those examined in this thesis, would widen the scope of the experimental results. Further, expanding the applications of sensory substitution for force feedback into other research areas such as rehabilitation engineering and other environments where a human is in contact with the environment through a mechanical or electrical interface, would demonstrate the generality of using sensory substitution for force feedback.

The results of this thesis indicated that sensory substitution for force feedback through the auditory and tactile modalities could be used for remote manipulator systems, and be flexible enough to accommodate a variety of tasks and users. The potential benefits of sensory substitution could be expanded to include many applications of remote manipulation in hazardous environments (nuclear, undersea, space, etc), as well as aiding those who are deficient in some sensory modality or are physically handicapped.

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