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A VIBROTACTILE DISPLAY FOR AIDING EXTRAVEHICULAR ACTIVITY (EVA) NAVIGATION IN SPACE

by

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A.B., Physics, Mount Holyoke College (1994)

Submitted in Partial Fulfillment of the Requirements for the Degree of
Master of Science
in
Aeronautics and Astronautics
at the
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ABSTRACT

A tactile display to increase an astronaut's situational awareness during an extravehicular activity (EVA) has been developed and ground tested. The Tactor Locator System (TLS) is a non-intrusive, intuitive display that can be configured to convey position information via a vibrotactile stimulus applied to the subject's torso region. In the Earth's 1-G environment, perception of position and velocity is determined by the body's individual sensory systems: the visual, vestibular and somatosensory systems (skin, muscle and joint sensors). Under normal sensory conditions, redundant information from these sensory systems provide humans with an accurate sense of their position and motion. However, altered environments, including exposure to weightlessness, can lead to conflicting visual and vestibular cues, resulting in decreased situational awareness. The TLS was designed to provide somatosensory cues to complement the visual system during EVA operations. An EVA task was simulated on a computer graphics workstation with a display of the International Space Station (ISS) and a target astronaut at an unknown location. Subject's were required to move about the ISS and acquire the target astronaut using either an auditory cue at the outset, or the TLS. Subject's used a 6 degree-of-freedom input device for translation and rotation. The TLS in this experiment was configured to act as a position aid, providing target direction information to the subject through a localized stimulus. Results show that the TLS decreases reaction time ($p = 0.001$) and movement time ($p = 0.001$) for subject (astronaut) movement about the ISS. The TLS is a useful aid in increasing an astronaut's situational awareness, and warrants further testing to explore other uses, tasks and configurations.

Thesis Supervisor: Dr. Dava J. Newman
Tile: Associate Professor of Aeronautics and Astronautics

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Nikol - thanks for being my sounding board and above all, the voice of reason (I think we have the boys figured out by now). Our talks and friendship has meant a lot to me and I most definitely wish that I could have you around more often. How can I possibly be expected to celebrate Mardi Gras without you?

Joelle - funny that they tried to keep us apart in the beginning when we turned out to be such amazing friends in the end. The good news is that I am impatiently awaiting the wedding announcement, but the bad news is that it just hasn't been the same since you left. Gros bisous sweetheart.

To my brother (well, close enough) Andy - I think I definitely kept my promise that I would look after you! I also think it's fair to say that no matter

how many years we keep playing, you definitely won the present game with that CD! Damn you for running off to play superhero for the Navy, but just wait until you get back - there will be no mercy!

Heather and Aimee, what would I have done if you had not become the surrogate daughters! I am so proud of you both for all that you have a accomplished, you truely are uncommon women. To Sharon - thank God there's someone looking out for me around here! There aren't enough thanks for all that you have done.

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Well, Ray thanks for bailing me out and becoming my kept man for a week (or should you be thanking me??). Our friendship has become very special to me, and since we missed out on the first two years, it's a good thing that you'll be sticking around for a while.

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1. INTRODUCTION

Humans have an advanced network of sensory mechanisms to maintain an accurate sense of situation awareness (SA), or position, velocity and orientation with respect to inertial space. These sensory systems have evolved to perform optimally in the Earth's 1-G environment, with motion typically confined to the surface of the planet. However, with the dawn of human flight and space travel came unusual sensory environments (greater degrees-of-freedom of movement, large and sustained accelerations, microgravity), that presented many challenges to these sensory mechanisms and leading to a new discipline, namely, aerospace physiology.

Exposure to unusual environments can often lead to disorientation. Aerospace physiological research tries to understand the response of human orientation mechanisms to unfamiliar environments in an effort to maintain SA. Unfortunately, environmental changes are experienced in many situations where disorientation is not only untimely, but life threatening as well. Within aerospace, spatial disorientation (SD) has become the leading cause of pilot mishaps in the military and of astronauts' space motion sickness among [Rupert, 1995]. SD occurs when pilots or astronauts incorrectly perceive the attitude, altitude or motion of their aircraft or of themselves, relative to the Earth or other significant objects.

A more complete and general definition of situation awareness is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future [Endsley, 1995]." Using this definition, if SD occurs, the projection of future status is jeopardized, and incorrect control decisions can be made. Human factors engineering has played a vital role in the development of pilot/astronaut displays and aides, to reduce the likelihood of incorrect perception. Although pilots and astronauts undergo extensive training, Endsley goes on the explain that "even the best-trained decision makers will make the wrong decisions if they have inaccurate or incomplete SA." A vibrotactile display that was proposed to increase one's SA has been developed and tested. The challenges ahead for the International Space Station (ISS) astronauts in the space program combined with the unique characteristics of the vibrotactile display, make it well suited for space applications. The goal of this thesis research is to examine the physiological, SA and human factors characteristics that drove the display design, and test the display's ability to increase the SA of an astronaut engaged in Extravehicular Activity (EVA).

1.1 Motivation

With the construction of the ISS, the number of astronaut Extravehicular Activities (EVA's) required will increase by a factor of five over those currently conducted for the Shuttle program (see Figure 1.1.1). The tasks to be performed range from the piece-by-piece construction of the ISS to its maintenance once the station is operational.

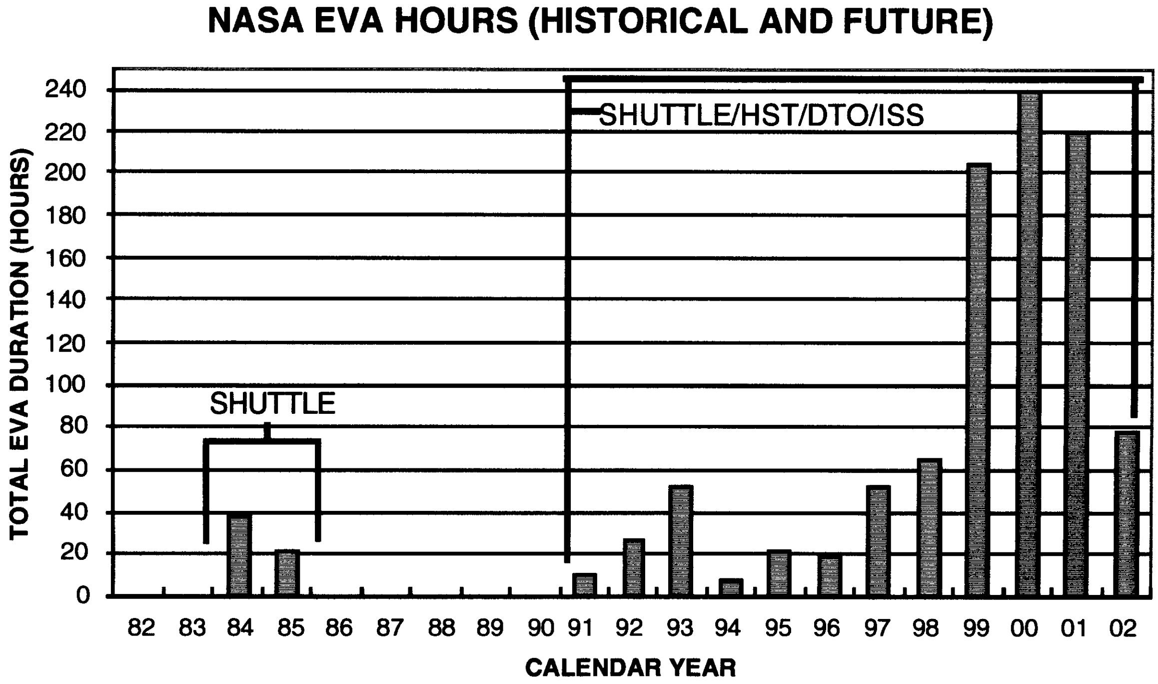


Figure 1.1.1 NASA EVA hours for the Shuttle program, including the projections for the ISS missions [EVA Office; Advanced EVA Research and Development; http://www.jsc.nasa.gov/xa/advanced.html].

During EVA, it is important that the astronaut maintains a high a level of situation awareness. In the Earth's 1-G environment, perception of position and orientation is determined by the CNS through receiving and interpreting redundant information from the body's individual sensory systems: the visual, vestibular and somatosensory systems (skin, muscle and joint sensors). However, exposure to weightlessness can lead to conflicting sensory cues, resulting in decreased SA. Rupert, et. al. (1994) described how space flight, along with military aviation and underwater exploration brings about changes in the sensory environment, leading to spatial disorientation. A jet pilot undergoing continual changes in acceleration will obtain false vestibular and somatosensory information about the perceived direction of "down," and therefore must rely increasingly upon her visual information to resolve conflicts. An underwater diver does not receive the strong somatosensory pressure cues experienced on the earth's surface, and an astronaut moving about in space loses all gravitational cues. In both cases, the reliability of vestibular system to provide accurate orientation information is reduced. An astronaut must therefore rely on the visual and somatosensory system for motion and position information. Unfortunately, in all of these examples, the visual system is typically busy with primary task performance considerations (piloting and navigating), yet it must simultaneously compensate for altered proprioceptive cues. The importance of feedback from displays and the environment to ensure SA in disorienting circumstances cannot be underestimated or compromised. Still, many of the current displays (attitude indicators, altitude and speed indicators, pressure gauges, etc.) designed to provide the human with situational feedback continue to employ the visual system. While it is evident that the visual modality is relied upon heavily, an additional concern arises because in many cases peripheral vision itself is occluded by suit and helmet restrictions.

Situation awareness is aided during Space Shuttle EVA's for several reasons: All EVA's are conducted in or near the cargo bay and air lock, while in full view of intravehicular (IV) crew members. Second, astronauts are always tethered to the cargo bay railings and often attached to the robotic arm, giving the astronauts near the cargo bay a common reference frame. In contrast, maintaining situational awareness during a station EVA will present many new challenges. Much attention had been devoted to EVA requirements for the ISS, including life-support requirements, training hours, EVA hours and crew safety requirements. Perhaps the most noticeable distinction between the Shuttle and ISS is the shear size and complexity of the space station structure (with an area of approximately 110m x 75m, roughly 1.5 football fields) [Gates, 1996]. (See Figure 1.1.2)

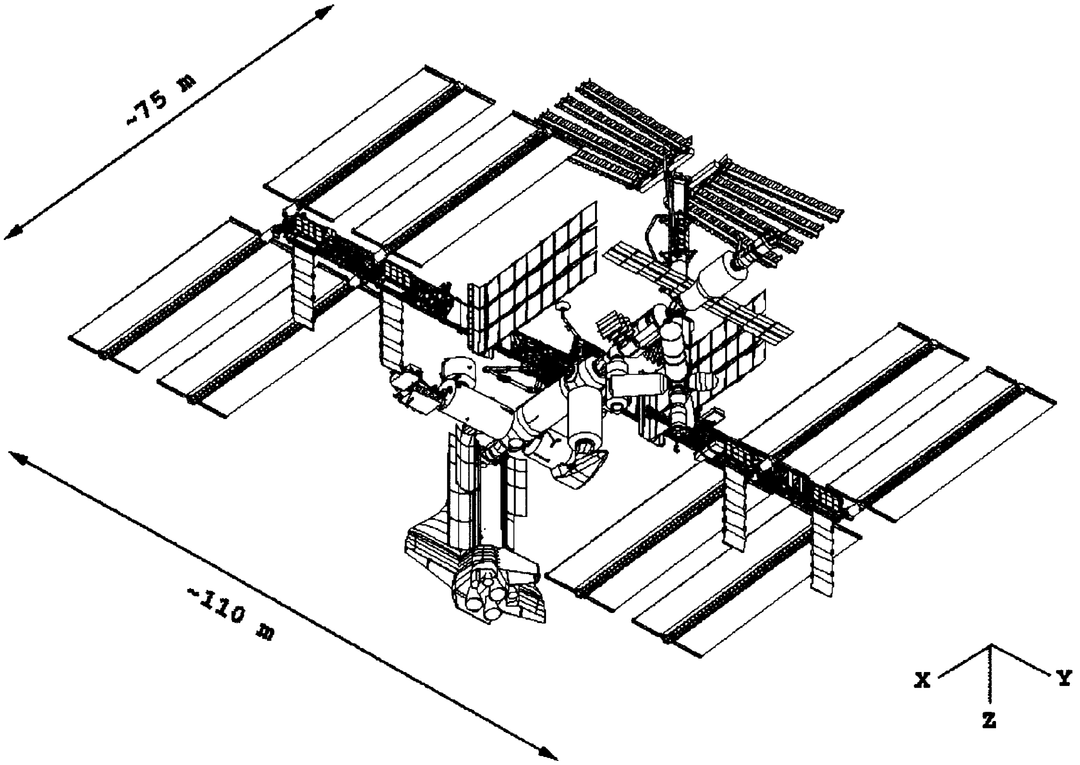


Figure 1.1.2 International Space Station Assembly (c77-1e+or) (http://semda.jsc.nasa.gov/).

As a result of these structural attributes, astronauts working on the ISS may not be in view of the air lock, IV crew members, or each other, and could be a considerable distance away from either. Since astronauts may be working in different areas of the ISS, the common reference frame (that the Shuttle previously afforded) is absent.

In 1991, Brody, *et al.* quantified the various costs associated with the separation of an astronaut from the space station. Of the three possible retrieval solutions Brody addressed, manned, robotic or self, it was determined that self-retrieval was the most economic in terms of fuel, time, and complexity, but that the human factors and SA issues associated with self-retrieval presented the most serious obstacles, even with the advent of the

Simplified Aid for EVA Rescue (SAFER) units. SAFER, intended for contingency use only, was designed as a self-rescue device for separated EVA astronauts when the Space Shuttle is unable to maneuver for a rescue (see Figure 1.1.3).

Figure 1.1.3 The SAFER unit [Bailey, 1996].

The Space Shuttle docked at the ISS is one example where SAFER units will be worn by all astronauts conducting EVA's. Whereas the SAFER unit is a smaller and simplified version of the Manned Maneuvering Unit (MMU), it lacks the propellant capacity and redundancy of the MMU [Bailey, 1996]. In the event of astronaut separation from the ISS, "the EVA crewperson must be able to ascertain [her position] and orientation with respect to the space station." As the time required for the astronaut to recover from tumbling or unusual orientation increases, so does the time and fuel required. It is desirable then, to assist the astronaut by giving her information regarding her orientation with respect to the space station.

Woods explained how EVA crew autonomy was found to be an important design driver for space station EVA systems (1995). "To maximize the overall productivity of the crew they need to be provided with all the resources to operate independently from the ground, as well as to allow the EVA crew to operate independently from the IV crew". Giving the astronauts a method of navigating autonomously would reduce the demands on the data management system, communication system, provisioning and training.

It is clear that astronauts conducting ISS EVA's are in need of an additional aid to assist in navigation, tracking and orientation. The Naval Aerospace Medical Research Laboratory (NAMRL) in Pensacola, FL has developed and tested (within the aviation community) the Tactor Locator System (TLS). The TLS is a non-intrusive, intuitive display that can be configured to convey position, velocity, orientation and tracking information via a vibrotactile stimulus applied to the torso region. It is important at this point to recognize that the TLS display does not increase visual workload as it provides somatosensory cues to *complement* the visual system. This research effort, discussed further in sections 1.2, Thesis Objectives and 1.3, Contribution of Thesis, explores the ability of the TLS to enhance the SA of an astronaut conducting an EVA, and specifically, the task of transporting to a target point quickly and efficiently.

1.2 Thesis Objectives

The primary objective of this research is to test the TLS's ability to act as a navigation aid by conveying position information to an EVA crewperson during a time critical task. It is hypothesized that this display will increase an astronaut's SA to allow for greater EVA crew autonomy, faster recovery of separated astronauts, and more efficient use of crew time and resources. The TLS must rely on independent navigation technology and therefore an investigation of the Global Positioning System (GPS) and Inertial Navigation System (INS) was made to assess the feasibility of having self-contained, navigation hardware system integrated with the vibrotactile technology (detailed in chapter 2, Background).

1.3 Contribution of Thesis

This thesis research introduces and asseses the utility of an innovative tactile display for use by an EVA astronaut on the ISS. The design and construction of the ISS is perhaps one of the largest technological undertakings of our time; presenting many obstacles to the engineers designing the station, as well as the astronauts living, working and maintaining the station. The introduction of a tactile display serves to bring EVA technology into the twenty-first century to meet the new demands the ISS will place on the astronauts, and ensure EVA crew safety and efficiency. The TLS, including a specified GPS/INS navigation system, is unique in that it is self-contained, unobtrusive, intuitive and reconfigurable to aid the EVA crewmen in a variety of capacities.

The thesis experiments described herein were designed to simulate a condition where the SA of an astronaut is degraded, that of maneuvering about the ISS, and test a device that claims to increase their level of SA. Directing the subject to perform a target acquisition task requires the subject to perceive and comprehend their environment, asses their future state, and make a control action; steps consistent with acquiring increasing levels of SA in dynamic situations. Measurements of Reaction Time (RT) and Movement Time (MT) can asses the ability of the TLS to increase SA against a control, in this case, and auditory cue (as it also complements the visual system). This comparison can be made, because a subject with a more complete SA will be able to react and maneuver more quickly and efficiently than a subject with incomplete or inaccurate SA.

1.4 Organization of Thesis

Chapter two, Background, provides information on three topics: situational awareness, navigation and the somatosensory system with regard to tactile displays. The section on SA contains a more detailed discussion of the mechanisms by which humans discern their orientation, namely, the vestibular, visual and somatosensory systems, as well as the conflicts leading to SD and space motion sickness. The navigation section discusses methods for navigation on Earth and in space, including an analysis of the GPS/INS system operational capabilities in both environments. Finally, a discussion of the physiology behind tactile perception and currently available tactile displays is presented. Chapter three, Pilot Study, discusses the preliminary study conducted prior to the ISS EVA experiment designed to test the ability of six tactors to convey 3 dimensional (3D) direction information to the subject. Chapter four, Methods describes the thesis experiment itself in detail. The first section describes the methodology and experiment scenario, then the description of the experimental hardware, protocol, and data analysis techniques is given. Chapter four, Results and Discussion, presents the results of the experimental data analysis, followed by a discussion of those results. Chapter five presents a summary of the work and conclusions drawn from the research, as well as some suggestions and recommendations for future work.

2. BACKGROUND

2.1 Situation Awareness

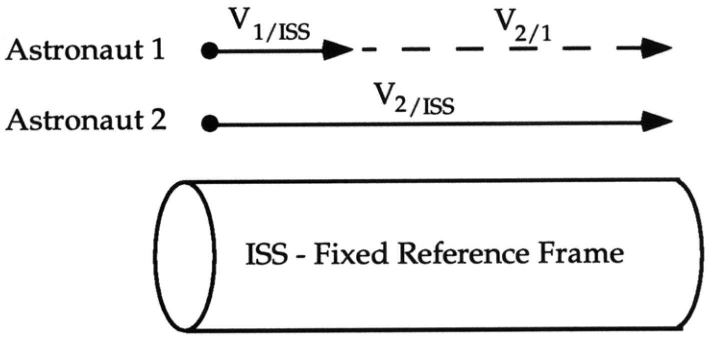
The physiological systems responsible for perception of motion, position and orientation (see Table 2.1 and Figure 2.1) are the visual, vestibular and somatosensory systems.

Table 2.1 Distinction between motion, position and orientation.

MOTION	Sensory systems' measurement of absolute linear or angular velocity (w.r.t. inertial space, global or local reference frame - the ISS frame for example) and velocity relative to other moving objects (i.e., another EVA astronaut).
POSITION	Position determination requires the integration of a velocity measurement to determine absolute position w.r.t. inertial space or fixed reference frame, and relative position w.r.t. other important objects (such as a target, the airlock, etc.).
ORIENTATION	Measure or description of the rotation of one axis (for example, an astronaut's body axis) relative to another (such as the ISS).

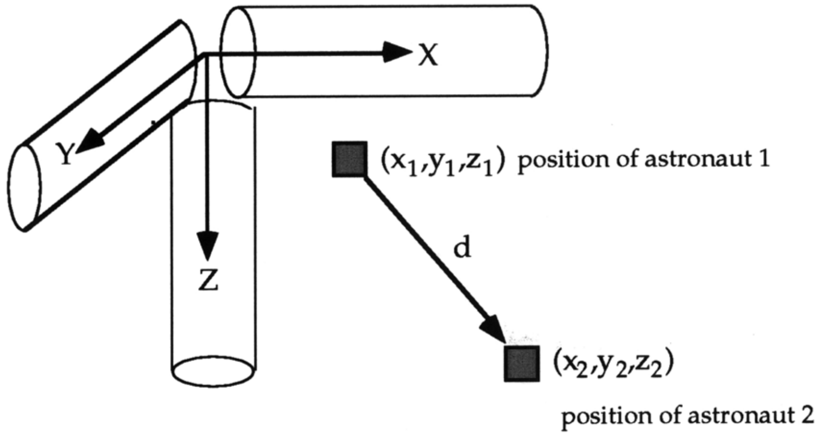
These systems are utilized as an astronaut attains level 1 SA - perception of the elements in the environment, and level 2 SA - comprehension of the current situation, and level 3 SA - projection of future status [Endsley, 1995]. In level 1, the astronaut gathers information regarding the status, attributes and dynamics of herself and the environment from the independent sensory systems and in level 2, combines this "disjointed" information into an understanding of the significance of those elements to the task at hand. This section describes how these physiological systems function in the Earth's "normal" 1-G environment, and how functions are altered in the microgravity environment of space, leading in many cases to erroneous information gathering and integration.

MOTION (VELOCITY)



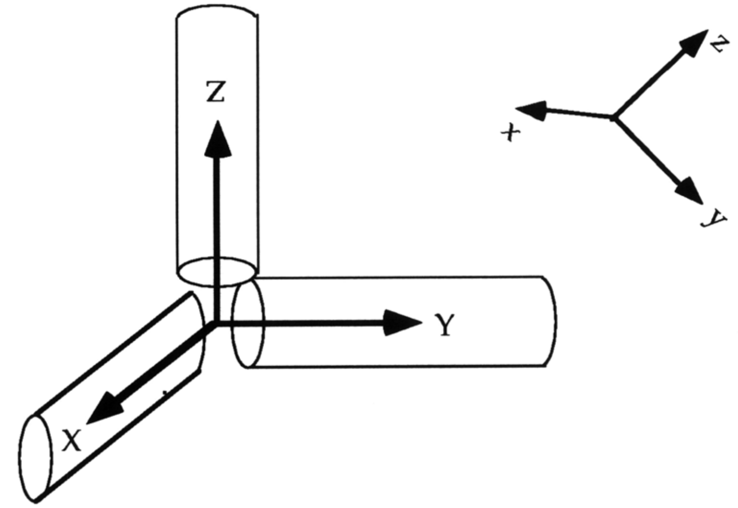
$V_{B/A}$ = the velocity of B with respect to A

POSITION



d = distance between astronaut1 and 2 (dependent upon motion information for both astronauts)

ORIENTATION



requires a coordinate transformation to describe the rotated frames' orientation relative to the ISS

Figure 2.1 Schematic of examples of velocity, position and orientation.

2.1.1 The Vestibular System

The vestibular system, the balance mechanism in the inner ear, consists of two organs; the semi-circular canals and the otoliths. The three orthogonal, fluid-filled canals estimate angular rates of the head with respect to inertial space, while the otoliths are responsible for measuring the orientation of the head with respect to gravity. To this end, the canals act as internal rate gyroscopes, or angular accelerometers, and the otoliths act as linear accelerometers and are discussed in detail in the section below.

2.1.1.1 The Semi-Circular Canals

Each of the orthogonal canals is filled with a viscous fluid called the endolymph. An input of head rotation about any axis will cause the canals in the plane of motion to rotate (see Figure 2.1.1). The endolymph, however, will lag behind the canal walls, resulting in a relative fluid shift in the direction opposite to that of the head rotation. The endolymph then pushes against, and creates a pressure difference across, the cupula (a gelatinous membrane sealing the canal) and likewise displaces it in the direction opposite rotation [Boff, Lincoln 1968]. Finally, tiny sensory hair cells in the base of the cupula output the pressure difference across it, signaling angular acceleration.

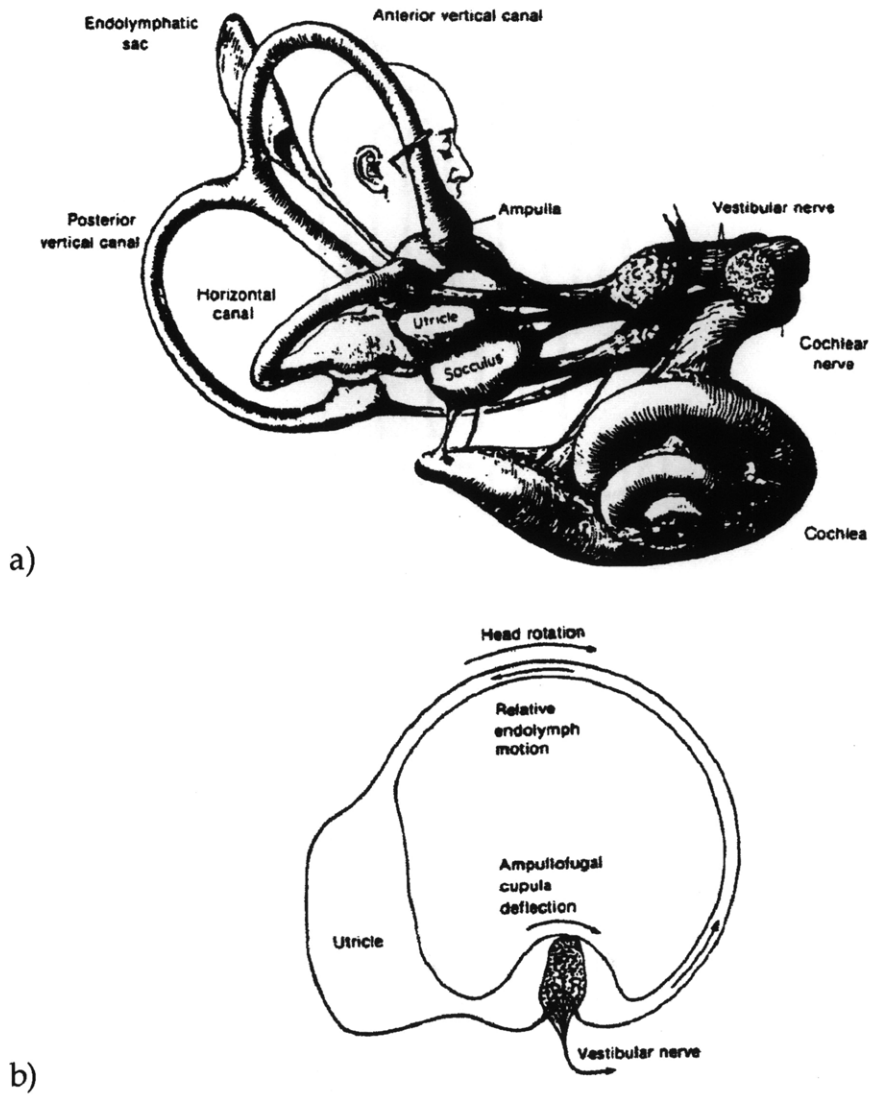


Figure 2.1.1 a) Diagram of the inner ear and position with respect to the head and b) a view of one semi-circular canal and its fluid circuit [Boff, 1988].

In actuality, the physical properties of the viscous fluid moving through the narrow canal induces the system to output angular velocities rather than angular accelerations (within the frequency range of nominal head movements, approximately 0.1-10Hz). When the head is angularly accelerated, the fluid rate (relative to the head) is proportional to the acceleration, therefore the position of the endolymph is proportional to the angular velocity of the head. At low frequencies (<0.1 Hz) the system acts as an angular accelerometer. The viscous forces that were significant at higher frequencies become negligible in this situation, and the mechanical properties of the cupula now dominate. The spring-like cupula provides a weak restoring force (with a time constant of approximately ten s), therefore during sustained constant rotation there will be no relative motion of the fluid with respect to the canal wall, and the cupula will eventually deflect back to its initial position [Wilson and Jones, 1979]. As a result, the CNS is no longer being signaled that the body is undergoing rotation, and the sensation of rotation damps out as the cupula returns to its equilibrium position. Consequently, Young explained, "we are led to experience some common illusions, including the sensation of flying 'straight and level' when our airplane takes a long continuous turn in the clouds or the sensation of spinning in the opposite direction when we are stopped after having been whirled about for a minute or so" (1982).

2.1.1.2 The Otoliths

The otolith organs are the primary non-visual determinants of static orientation with respect to the vertical. In addition they act in conjunction with the vertical semi-circular canals to indicate changes in orientation and initiate corrective postural responses [Young 1982]. Whereas the canals are highly proficient angular accelerometers, they do not sense linear accelerations, nor do they give an accurate reading of the orientation of the head with respect to gravity. The organs responsible for these tasks are the utricular and saccular otoliths. The utricular and saccular maculae contain the sensory end organs, or hair cells called cilia [Boff, Lincoln 1988]. Figure 2.1.2 shows the orientation of the maculae in the otolith organs, with respect to the head.

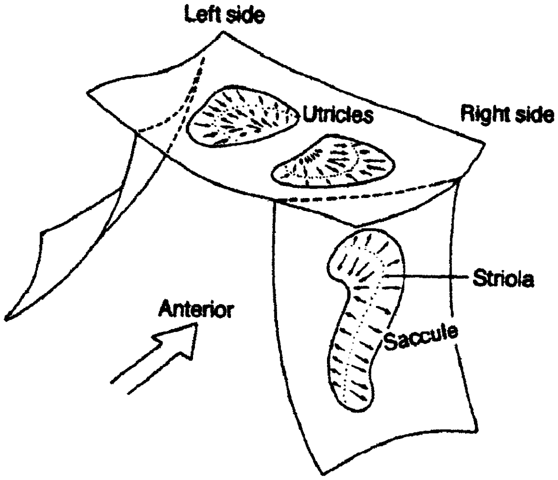


Figure 2.1.2 Orientation of the maculae in the otolith organs with respect to the head (arrow indicates polarization) [Boff, 1988].

The cilia extrude into the statoconial membrane upon which rests a layer of calcite crystals called otoconia. In response to either head tilt or linear acceleration, a shear force is generated by the otoconial mass and the cilia are subsequently deflected from their equilibrium position, increasing the firing rate of the receptor cells. The net acceleration measured is the vector resultant of gravity and inertia (resulting from the acceleration) (see Figure 2.1.3). In essence, for horizontal head tilt and linear acceleration (a) the resultant gravitational force vector (g) is rotated in the direction of motion through an angle equal to the arctan of a/g, and its magnitude increases to $\sqrt{(a^2 + g^2)}$ [Arrott et.al. 1990, Polutchko 1993].

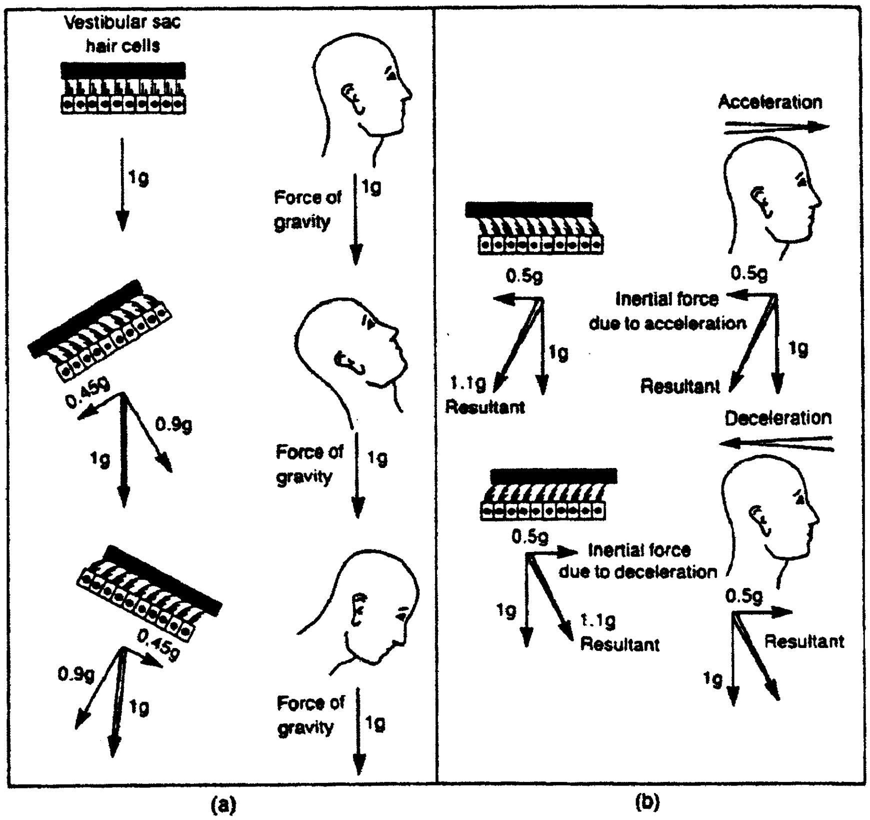


Figure 2.1.3 The forces acting on the otolith organs during a) tilt about the y-axis and b) during linear acceleration in the x-axis of the head [Boff, 1988].

There is however, an ambiguity, shown in the previous Figure, that the effect of horizontal linear acceleration is indistinguishable from the effect of tilting the head through an angle whose sine is a. This ambiguity is the leading human factors cause of carrier mishaps. Launching off of an aircraft carrier at great speeds, the pilot feels as though he is severely pitched up, when in reality he is being forcefully pressed back into their seat due to the large acceleration. Consequently, the pilot may throw the nose down to avoid any risk of stalling the aircraft, thereby crashing into the ocean below. In the absence of any dominant visual cues (i.e., night flying) this vestibular illusion can be quite compelling and can have disastrous consequences. Lastly, as will be discussed further in section 2.1.4, EVA Considerations, vestibular function is degraded in weightlessness, as the otolith organs assume a static position that can no longer provide a meaningful reference to the vertical [Young

1982, Oman 1982]. Along with visual and vestibular, somatosensory (tactile and proprioceptive) cues aid us in discerning our spatial orientation. "Tactile and proprioceptive cues encode pressure against the skin, limb position and muscle length and tension [Young 1982]."

2.1.2 The Somatosensory System

Working in conjunction with the vestibular system, the somatosensory is also responsible for sensory inputs to determine one's SA. For example accelerating in a car, the visual system reports the motion of the outside scene, the otoliths sense the linear acceleration, and the somatosensory system senses the pressure increase on the back and butt as the driver is pressed into the seat. In the weightless environment however, our muscle and joint sensors are no longer receiving the constant pull of gravitational acceleration to remind us of "down". Familiar 1-G movements if executed in microgravity would be inappropriate and possibly hazardous, however, our bodies adapt quickly to locomote optimally in weightlessness [Newman *et al*, 1994]. Astronauts in microgravity rely almost entirely upon concentrated upper body movements for locomotion, while the larger muscles in the legs are continually deconditioning, combated only with daily exercise.

Tactile stimuli in the form of pressure or mechanical cues to the surface of the skin can be effective for detecting changes in applied force, however the skin adapts rapidly and is therefore not effective at detecting sustained stimulation. For example, clothes put on in the morning are felt initially but are not felt throughout the day, as the skin adapts to the sensation. Therefore in order to maintain a steady-state sense of orientation in the weightless environment, one must rely on the altered sensory inputs of limb position, muscle length and tension, rather than pressure cues [Young 1982].

2.1.3 Sensory Conflict Theory

The previous sections presented the background on how the environmental elements are assessed (level 1 SA), but how are the individual perceptions integrated to form higher levels of SA, and when does this integration lead to false or incomplete SA? In nominal sensory environments, the body's sensory systems described above give redundant cues, whereas in unusual sensory environments (such as higher degrees of freedom of movement, large and sustained accelerations, and weightlessness), two or more sensory modalities may give conflicting orientation cues. As in the earlier aviation example, the visual system may see the artificial horizon indicator reading a nominal pitch on takeoff, but the vestibular system senses that the aircraft is at an angle of attack approaching stall. In such situations, the central nervous system (CNS), responsible for integrating incoming sensory information and producing command signals, must determine the relative weighting of the conflicting signals. This concept has come to be known as the "sensory conflict theory" [Oman, 1982, 1996].

Both on Earth and in microgravity, when the CNS is forced to resolve and weight conflicting information, motion sickness is more often than not, the resultant effect. For example, passengers standing in a cabin on a rocking boat receive vestibular cues indicating the motion of the ship, however, since the eyes move with the room the visual indicates the contrary, that of being stationary, and motion sickness can develop. One remedy suggested to passengers is to look at the horizon so that the visual system can recognize and signal the motion as well. During the series of missions comprising the ten year Spacelab program, approximately 70% of astronauts reported symptoms of space motion sickness (SMS) in the early days of orbital flight missions [Young and Seddon, 1994]. The stimulus eliciting SMS symptoms is now believed to be a function of the difference between the actual and expected sensory organ responses as astronauts try to move about the weightless cabin environment as if they were in a 1-G environment. One of the leading causes of SMS has been head movements (particularly in pitch and roll), because the otoliths are no longer providing a response to head tilt [Oman 1996].

One visual illusion that occurs frequently on Shuttle missions involves the astronauts' assignment of "walls" and of a "floor" or "ceiling" to the cabin in an effort to provide themselves with a fixed frame of reference. Typically, the surface in the lower field of view or in the direction of the feet is thought of as a local "floor", and the astronaut might choose to adopt that as a particular reference orientation. However, viewing another astronaut inverted or the earth overhead through the flight deck windows, can cause some astronauts to feel suddenly "upside down". In the absence of a concurring vestibular cue, this shift in orientation perception can result in SMS. Given that the presence of a local "down" varies as the astronaut moves throughout the cabin, it is not surprising that astronauts have reported quickly losing their orientation within the cabin in the absence of visual or tactile cues [Oman 1996, Oman 1982]. Likewise, outside of the cabin during an EVA, astronauts are apt to assign a local "down" in the direction of their feet, and seeing another astronaut in a different orientation, or having to change orientations suddenly may quickly lead to spatial disorientation.

2.1.4 EVA Considerations

Up to this point the discussion has centered mainly around the behavior of and illusions experienced by IV crewmembers, however, there are many important SA factors that must be accounted for when an astronaut is conducting an EVA. Although no EVA's are scheduled for the first few days of space flight, allowing time for the astronauts sensory organs to adjust to the weightless environment and overcome any SMS they may experience, spatial disorientation is still a concern, even for the most adapted crewmembers. With altered proprioceptive feedback and limited vestibular input, and for the ISS with more intense EVA requirements, it will be difficult for astronauts to preserve a steady-state (long-term) sense of their orientation. In spite of these difficulties, maintaining a particular reference frame can be of great assistance in retaining one's spatial orientation. Currently this is accomplished by restricting the astronauts to work only within the immediate vicinity of the Shuttle, and in constant view of the IV crewmembers. Given the size and complexity of the space station, the varying orientations of the modules and the number of different locations where EVA's will be conducted, a stable reference frame is not available. Furthermore, the appearance of the modules are such that they are relatively indistinguishable from one another, and may not afford opportunities for adopting a local reference frame. Finally, in the event of an emergency ingress or separation, any delays in regaining one's spatial orientation could be life threatening. This provides the motivation for developing the Tactor Locator System (described in detail below) for potential use in the ISS EVA program.

2.2 The Tactor Locator System

The experiments conducted on the Spacelab Life Sciences - 2 mission in 1993 showed that the CNS places the highest weighting on visual information in the absence of otolith tilt information [Young, 1995]. Perhaps the most obvious benefit of conveying information to an astronaut through the tactile modality rather than the visual modality, is that the visual system is already engaged in primary task performance. Young went on to say that "the mere presence of *any* tactile cue, even if it provided no information about the presence or absence of body tilt or direction of sway, served to inhibit the dependence on visual field motion in determining perceived self motion in space." With this in mind, the TLS could potentially relieve the visual system, but more importantly, aid the visual system in self-motion perception by providing a redundant sensory cue. In fact, the TLS can contribute position and velocity information (although velocity information is beyond the scope of this study). A sense of speed (for example, a breeze felt against the chest while moving forward) due to self-motion can be conveyed to the user through appropriate tactile patterns and frequencies.

In this thesis research effort, the TLS is configured to act as a position aid, that is to say, it gives the user a directional vector from herself to a target. Additionally, it is desired to find the minimum number of tactors required to convey this information accurately. The following sections discuss the impetus behind the TLS design and the spectrum of functions it performs.

2.2.1 The Tactile Modality and TLS Design Drivers

In the following sections, the characteristics of the tactile modality will be described, as well as how the design of the TLS exploits these attributes. Some general properties of the skin will be reviewed, including the ability of the skin to act as both a static and dynamic display.

2.2.1.1 General Properties

Some of the first research into conveying information through the skin was conducted in the late 1800's. Since that time, much has been learned about the properties of the skin as sensory channel, and in the 1950's and 60's, researchers began to utilize this new information to aid the visually impaired. As early as 1965, B. von Haller Gilmer had the vision that there might be a "practical need for a tactile communication [for] supplementing communication with astronauts in outer space". Gilmer also noted that "the skin as a sensory channel may have one completely unique aspect; it is rarely ever 'busy.'"

The tactile modality has several other characteristics that are important design drivers for the TLS. For example, the skin cannot accurately sense the absolute magnitude of an applied force because it adapts quickly to stimuli, but can sense changes in applied force. Tactile stimulators should not be placed in a location where the sensations could be masked by the physical manipulation required to complete the task; if one is trying to grasp an object in free space, the forces produced by the gripping motion of the hand would conceal the vibrotactile forces the operator was to use as a perceptive guide [Sheridan, 1992]. Therefore the 'hand over hand' method (one that the astronauts will be using to maneuver about the ISS modules) along hand rails, would mask any tactile stimulation applied to the hands or arms, as these are the primary means for locomotion in space (both for EVA and IVA) [Trevino 1992; Dutton, 1996]. Tactile stimulation elicits a reflexive action that immediately directs the human's attention to the area being stimulated; this serves as an important aspect of touch sensing in the event that an astronaut must be diverted away from her primary task quickly.

In 1991, Cholewiak and Collins [Cholewiak, Collins, 1991] summarized much of the previous research concerning the information properties of the skin including thresholds and adaption. An absolute threshold refers to the minimum energy stimulus that can be perceived, for a given subject and set of experimental conditions. Depending on the area of the body where the stimulus is applied, a vibratory stimulus with an amplitude as low as 0.2 microns can be perceived. Figure 2.2.1 shows the threshold response for pressure and vibration stimuli as a function of body locale using a 200Hz stimulus. It was discovered that the threshold for vibratory stimuli depended upon temperature and frequency, however, using a stimulus consisting of a train of pulses (at a constant temperature), the threshold was much less dependent on the rate of pulse presentation.

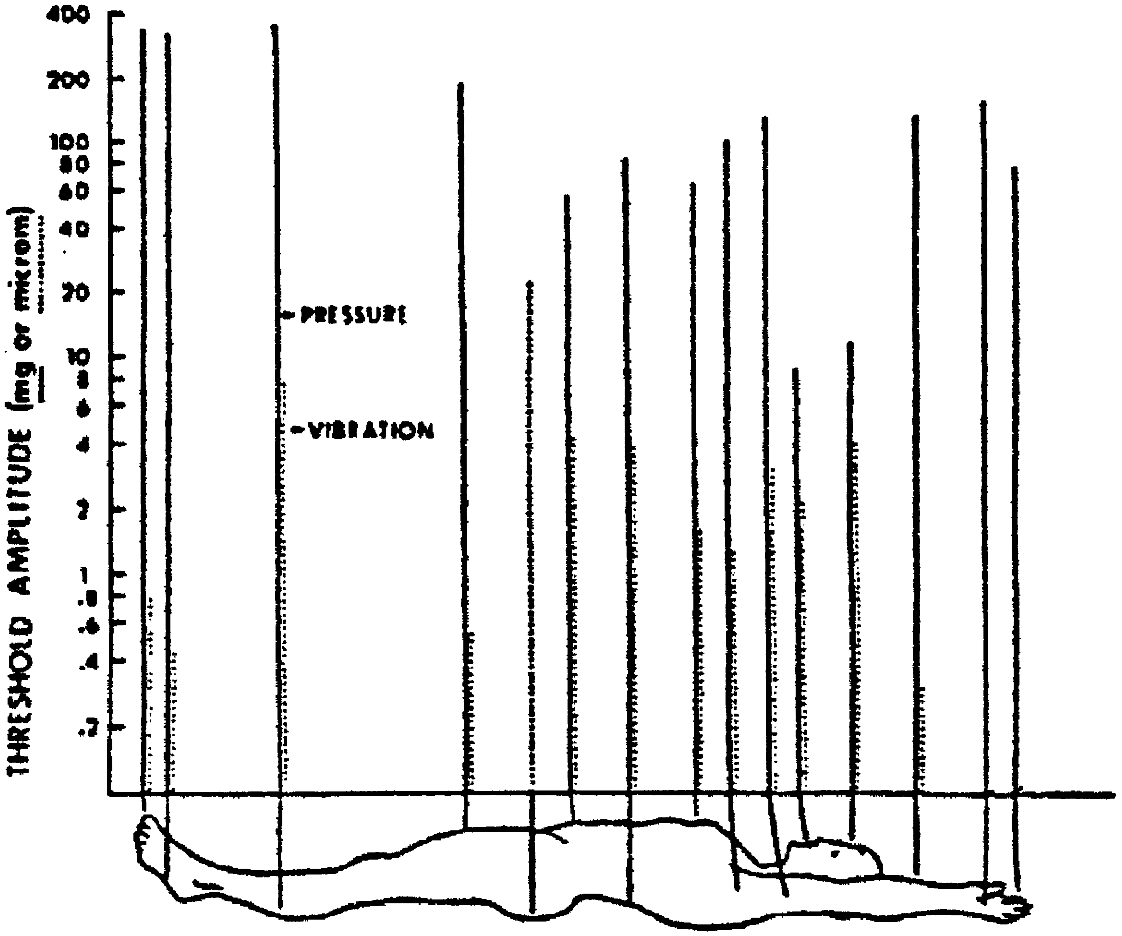


Figure 2.2.1 Threshold responses for pressure and vibration (200Hz stimuli) as a function of body site [Cholewiak & Collins, 1991].

In 1968, Weinstein studied the two-point discrimination and point localization thresholds over twenty areas of the body, for males and females (Figures 2.2.2and 2.2.3, respectively, show exemplary experimental results for females). Two-point discrimination refers to the distance apart that two distinct stimuli can be applied and resolved as occurring at two different points, as compared to a single stimuli.

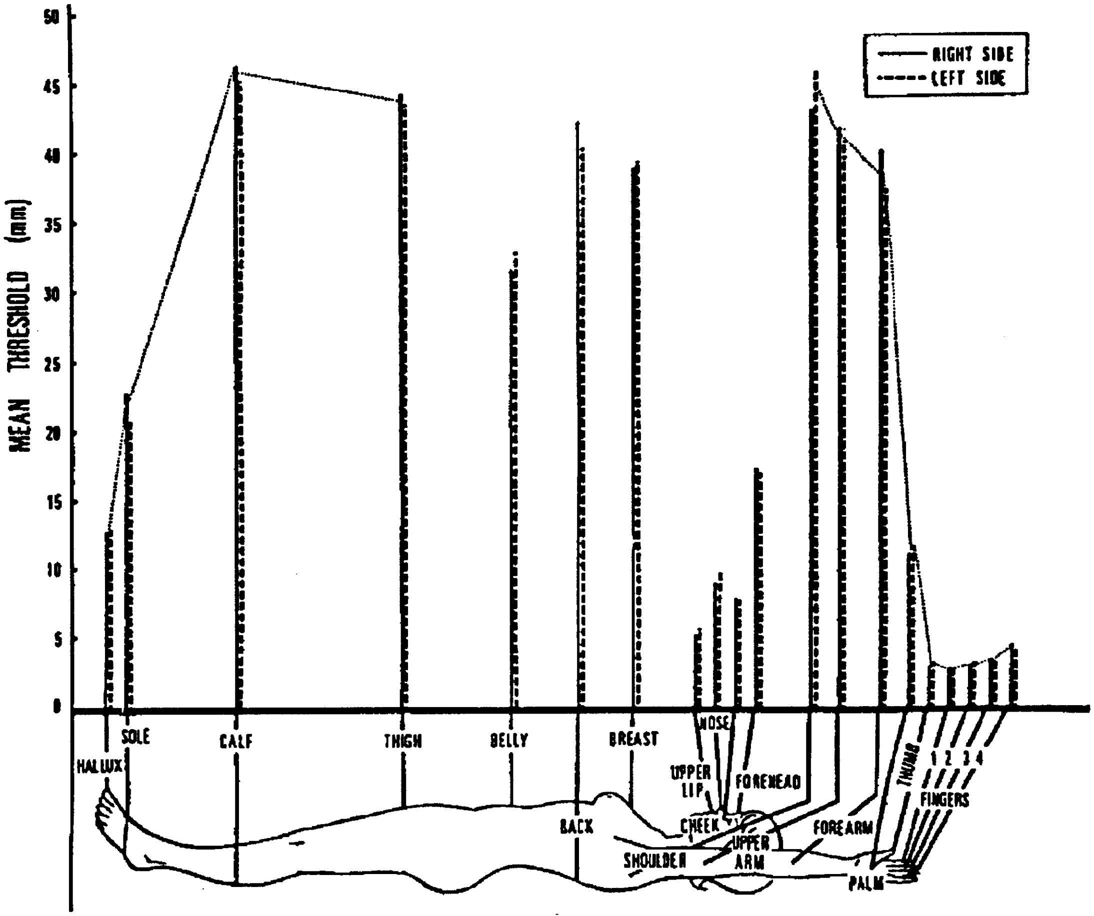


Figure 2.2.2 Two-point discrimination thresholds for females [Weinstein, 1968].

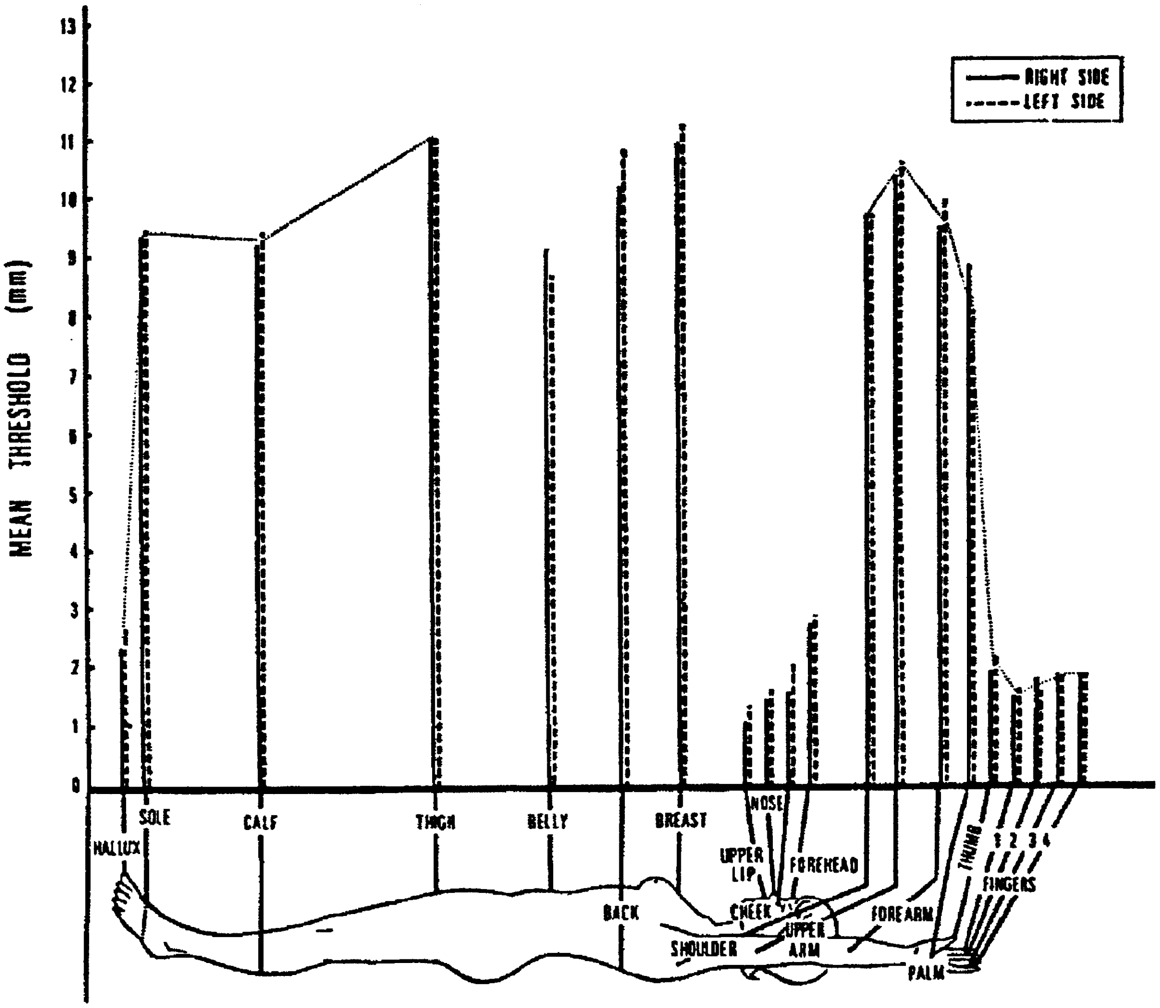
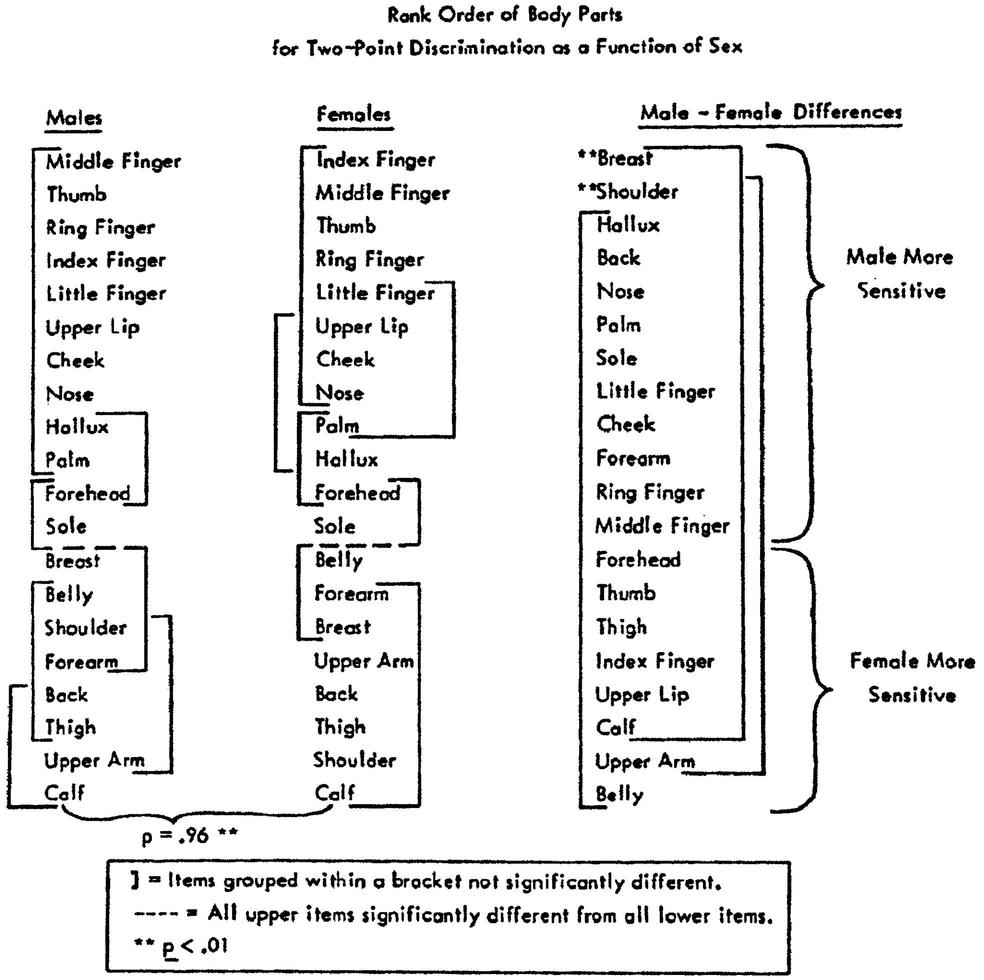


Figure 2.2.3 Point localization thresholds for females [Weinstein, 1968].

Specifically, subjects were required to identify (for a given body part and separation of the two stimuli) two double and two single stimulations presented in a random order. A smaller threshold signifies that two stimuli presented together can still be perceived as distinct at a smaller separation distance. In the point localization experiment, subjects were stimulated at a reference point at the center of a Y-shaped grid. Subsequent points on the branches of the Y were then stimulated, and the subjects asked if it too had been applied at the reference point. A smaller value of point localization threshold signifies that the subject is able to distinguish two stimuli applied at different locations for that part of the body. Weinstein found that, as might be expected, the hands and face were the most sensitive parts of the body across all subjects and experiments [Weinstien, 1968]. Table 2.2.1 and table 2.2.2 shows the rank order of the body parts for the two experiments, respectively.

Table 2.2.1 Rank order of body parts for two-point discrimination as a function of gender [Weinstein, 1968].



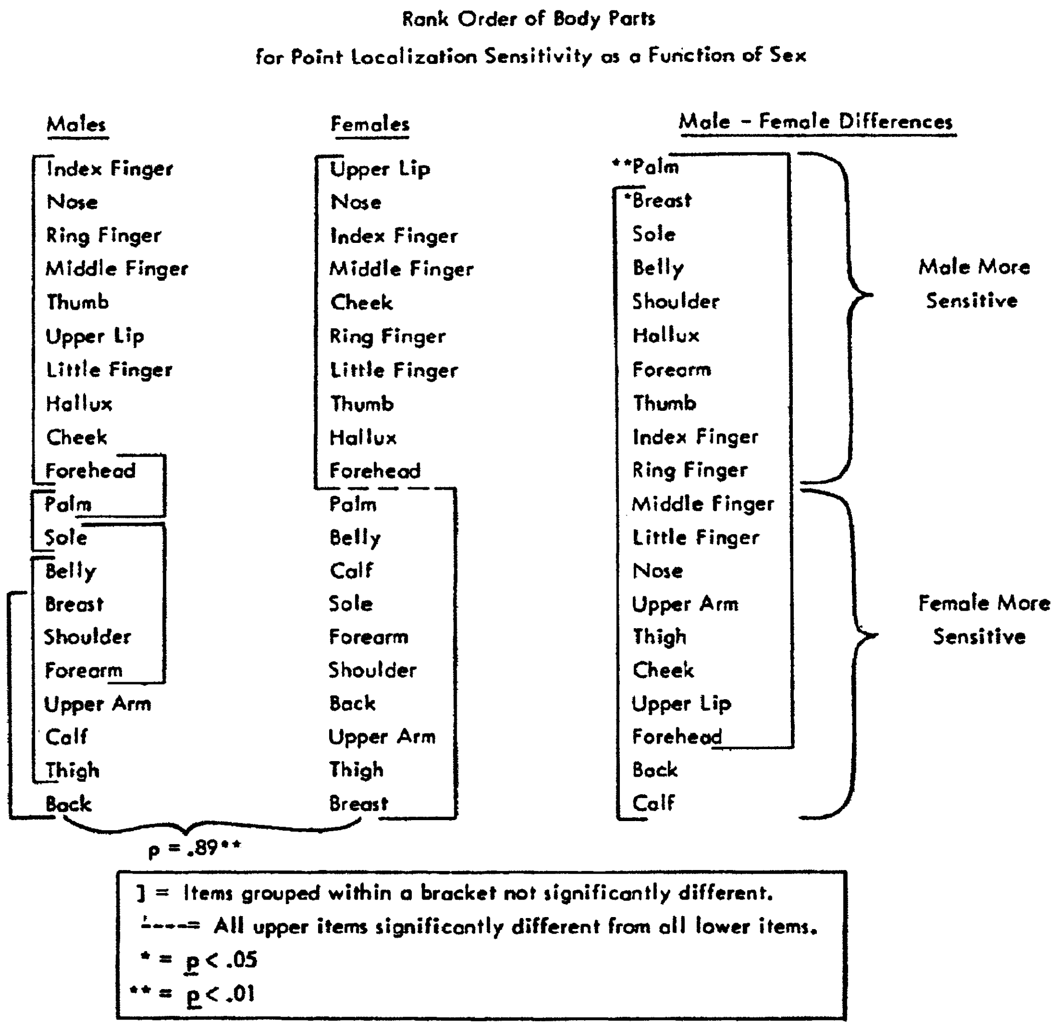
Rank Order of Body Parts
for Two-Point Discrimination as a Function of Sex

Males	Females	Male - Female Differences	
Middle Finger	Index Finger	**Breast	Male More Sensitive
Thumb	Middle Finger	**Shoulder	
Ring Finger	Thumb	Hallux	
Index Finger	Ring Finger	Back	
Little Finger	Little Finger	Nose	
Upper Lip	Upper Lip	Palm	
Cheek	Cheek	Sole	
Nose	Nose	Little Finger	
Hallux	Palm	Cheek	
Palm	Hallux	Forearm	
Forehead	Forehead	Ring Finger	
Sole	Sole	Middle Finger	
Breast	Belly	Forehead	Female More Sensitive
Belly	Forearm	Thumb	
Shoulder	Breast	Thigh	
Forearm	Upper Arm	Index Finger	
Back	Back	Upper Lip	
Thigh	Thigh	Calf	
Upper Arm	Shoulder	Upper Arm	
Calf	Calf	Belly	

p = .96 **

] = Items grouped within a bracket not significantly different.
---- = All upper items significantly different from all lower items.
** p < .01

Table 2.2.2 Rank order of body parts for point localization as a function of gender [Weinstein, 1968].



Rank Order of Body Parts
for Point Localization Sensitivity as a Function of Sex

Males	Females	Male - Female Differences	
Index Finger	Upper Lip	**Palm	Male More Sensitive
Nose	Nose	*Breast	
Ring Finger	Index Finger	Sole	
Middle Finger	Middle Finger	Belly	
Thumb	Cheek	Shoulder	
Upper Lip	Ring Finger	Hallux	
Little Finger	Little Finger	Forearm	
Hallux	Thumb	Thumb	
Cheek	Hallux	Index Finger	
Forehead	Forehead	Ring Finger	
Palm	Palm	Middle Finger	Female More Sensitive
Sole	Belly	Little Finger	
Belly	Calf	Nose	
Breast	Sole	Upper Arm	
Shoulder	Forearm	Thigh	
Forearm	Shoulder	Cheek	
Upper Arm	Back	Upper Lip	
Calf	Upper Arm	Forehead	
Thigh	Thigh	Back	
Back	Breast	Calf	

p = .89**

] = Items grouped within a bracket not significantly different.
----= All upper items significantly different from all lower items.
* = p < .05
** = p < .01

Notice in the previous table that for two-point discrimination there is a significant difference between the back and the breast, whereas the two areas not statistically different for the point localization experiment. As will become apparent when the 'phantom' sensation is discussed in section 2.2.1.2, Static Displays, it is significant that the point localization threshold does not differ around the torso.

Finally, *adaption,* is defined as an increase in threshold or the reduction in apparent intensity of a stimulus with prolonged stimulation. Adaption suggests that the TLS display should not be used throughout the duration of an EVA, but when ingress or translation to another worksite is required, or in the event of an emergency. If adaption occurs, there is no permanent damage to cutaneous skin receptors, as the time course of adaption follows a regular growth function. In addition, recovery progresses quickly once the stimulus is removed [Cholewiak, Collins, 1991]. The skin has additional exploitable characteristics that make it particularly well suited for displaying either static or dynamic information. The following sections discuss each of these modes in turn.

2.2.1.2 Static displays

In 1970, Alles agreed that the tactile modality had a high information capacity and studied the phenomenon that two equally loud (perceived intensity) tactile stimuli presented simultaneously to adjacent locations combine to form a sensation midway between the two tactors. He dubbed this the 'phantom' sensation and remarked that it was dependent upon the separation of the tactors, their relative amplitudes and their temporal order; a tactile equivalent to directional hearing [Alles, 1970]. Figure 2.2.4 shows the effect of interstimulus interval (time in milliseconds (ms) from end of the first stimulus to onset of the second stimulus) on the location of the phantom sensation. Surprisingly, Alles found that the phantom sensation can be obtained by two stimulators located anywhere on the body, although the sensation was more distinct when the stimuli were several inches apart [1970]. Figure 2.2.5 shows the relation between interstimulus interval and sensation, position, size and amplitude.

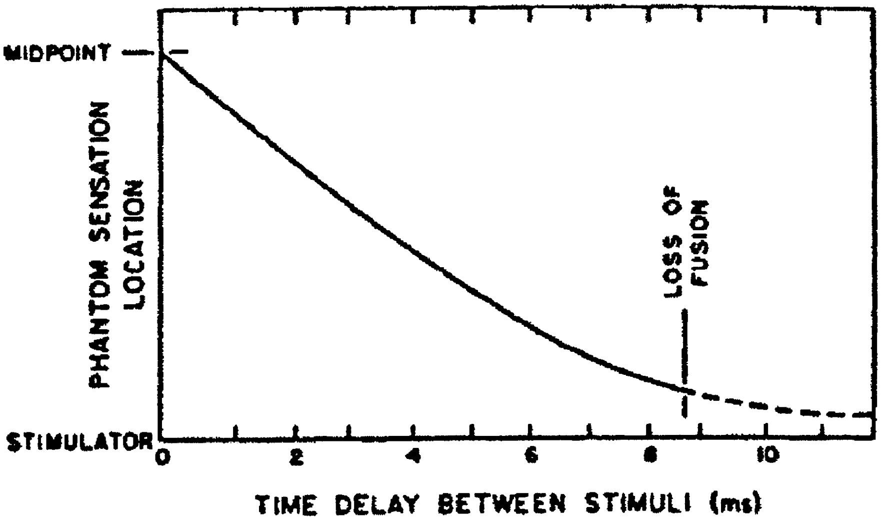


Figure 2.2.4 Effect of time delay on phantom sensation location [Alles, 1970].

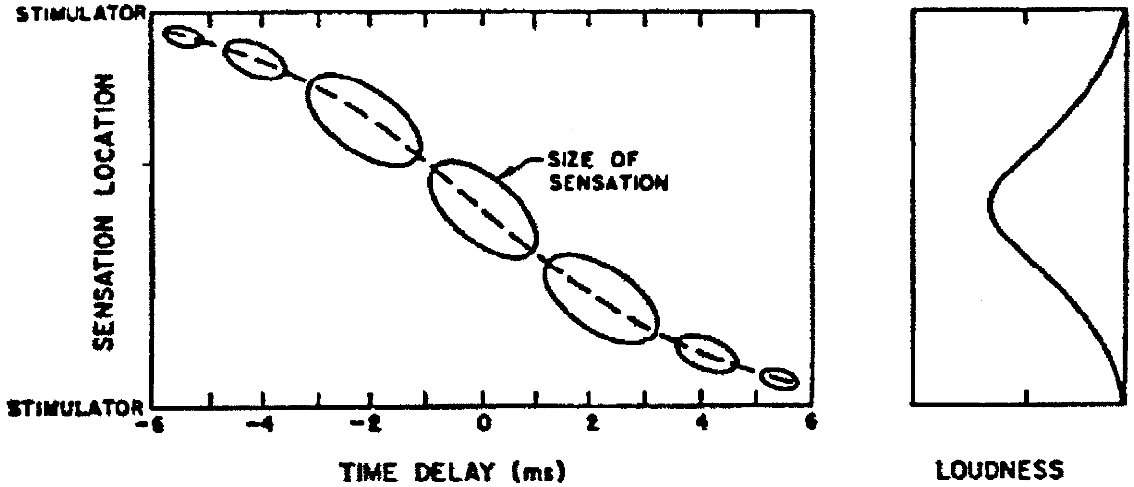


Figure 2.2.5 Graph of the relative size, loudness and location of the phantom sensation for varying time delays [Alles, 1970].

Notice that the size and loudness of the sensation occurs at the midpoint of the two individual stimulators in the absence of a time delay between pulses. Since it is desired to have the TLS convey the position vector of a target using a minimum number of tactors, the phantom sensation makes the resolution of two proximal vectors intuitive, allowing for fewer tactors.

Although, as will be detailed in section 2.2.1.3, Dynamic Displays, the TLS can indeed be configured to display directional flow information as Young suggested (1995), the position arrangement utilized in these experiments will be a static, rather than a dynamic display. In a static display all of the tactors that make up the desired pattern to be presented are turned on and off simultaneously [Craig & Sherrick, 1982]. Another type of static display that could be useful for the ISS EVA program is a tracking display. Due to the limited field of view of the EVA helmet (field of vision is 120 degrees left and right in the horizontal plane, 105 degrees down and 90 degrees up in the vertical plane), astronauts conducting space Shuttle EVA's can have difficulty tracking the navigation of their EVA team members [NASA-STD-3000 1994]. The TLS, independent of the resolution desired of the astronauts, could easily act as a navigation tracking device in this situation. A tracking display would be similar to the position display but would not require the resolution of vectors, due to the larger size and closer proximity of the "target". Therefore, a static display is required to pulse the user in the direction of their partner. The display is not to be used continuously, but rather for a discrete amount of time, to avoid any adaptation that may occur. Craig and Sherrick (1982) recounted experiments conducted testing several different displays for tracking accuracy. Experimenters commented that quantifiable comparisons could be made between targets tracked visually and tactually. While, not surprisingly, visual tracking in most situations was superior, tactile tracking accuracies approached if not equaled visual levels [Craig & Sherrick, 1982].

2.2.1.3 Dynamic Displays

In addition to acting as a static display, the TLS is also an excellent example of a dynamic display in a velocity data configuration. Since early Braille readers, tactile displays have been conveying movement and flow information through the cutaneous sensory channel. As discussed previously, astronauts have decreased directional flow information on orbit and are relying increasingly upon the visual channel to provide whatever data is required for successful locomotion. Cholewiak and Wollowitz [1992] remarked that there are three areas to be considered when designing a vibrotactile display for the purposes of communication; the overall properties of the skin, the variation of the skin's characteristics as a function of body site, and the effect of varying the stimulus characteristics at a given site.

As Kirman [1974] showed, two vibrotactile pulses presented quickly in succession are perceived as a moving source. Furthermore, varying the interstimulus onset interval (ISOI, defined as the time interval in msec between the onset of the first stimulus, and the onset of the second stimulus) and pulse duration can vary the degree of the apparent movement. Perhaps Kirman's most striking result was the confirmation that the function relating the pulse duration to the quality of the apparent movement is similar for the tactile and visual modalities as was originally discussed by Sherrick and Rogers [1966]. This may suggest that the conditions for apparent movement is independent of the modality and lend further credence to the use of the tactile modality to enhance sense of movement and SA.

In 1975, Verrillo and Gescheider looked at "Enhancement and summation in the perception of two successive vibrotactile stimuli [Verrillo & Gescheider, 1975]." Summation refers to the subjective perception of the overall magnitude of the two temporally spaced pulses, and enhancement refers to the increment in the subjective magnitude of one stimulus due to the presentation of another. Enhancement effects are maximized when the frequencies of the two tactile pulses are identical, and summation effects are maximized at greatly differing frequencies. Presenting two successive pulses of vibrotactile stimuli at equal frequencies can create the illusion that the second pulse is actually 'stronger' than the first. This sensation could be useful if the user was to be alerted to a target approaching by directing pulses radially inward towards the 'impact' point (see Figure 2.2.6). The cutaneous saltation effect, commonly referred to as the 'rabbit' illusion can create a 'hopping' sensation across the skin through a series of taps presented sequentially [Craig & Sherrick, 1982; Geldard, 1975; Geldard and Sherrick, 1972]. This illusion could likewise be useful for conveying motion through space by providing flow information.

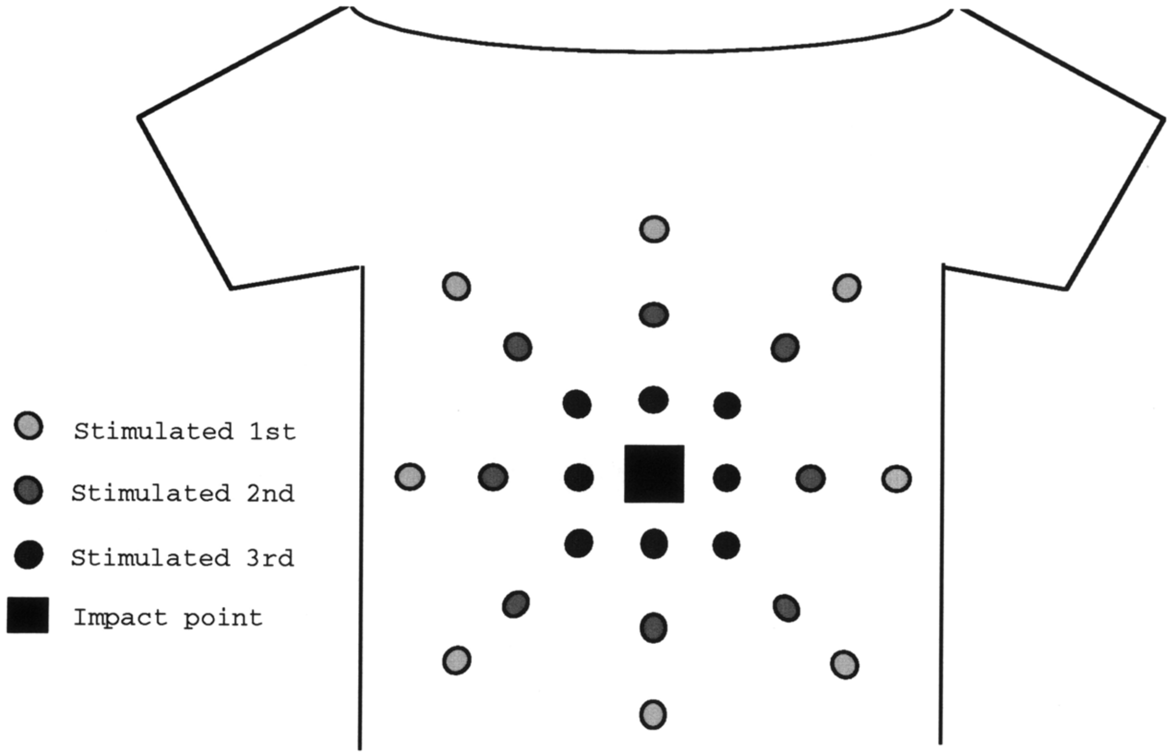


Figure 2.2.6 Schematic diagram of presenting successive pulses to warn user of impact, exploiting the enhancement effect.

From the literature we can conclude that the skin is indeed an appropriate sensory channel for transmitting both static and dynamic signals. Its properties, discussed throughout section 2.2, allow it to support communication of a wide range of information that can be interpreted quickly and intuitively as position, motion and/or orientation cues. In addition, while the TLS takes advantage of this sensory channel in the context of aiding EVA astronauts, as in this research application, its versatility can extend the skin's advantage to displays for other applications (as will be discussed in Chapter 6, Summary and Conclusions).

The final design component of the TLS, in addition to the physiological, is the autonomous navigation hardware. The navigation package must maintain an accurate reading of the position and orientation of the astronaut at all times in order for the TLS to be effective at increasing SA. The following sections describe the components of the package and presents a design solution for EVA applications (helicopter hover considerations are presented in Appendix D).

2.3 Navigation

In order to ensure that the TLS is both efficient and practical, it is necessary to incorporate an 'on-board' navigation solution that can be easily configured to satisfy the EVA requirements for a variety of missions. Fortunately, great strides are being made in navigational technology. The global positioning system (GPS) and inertial navigation have become standard practices with applications ranging from ballistic missile tracking to geophysical mapping of the Earth's terrain. The task of designing a navigation package to integrate with the TLS demands the very best of current technology for several reasons. Firstly, the system must be robust enough to handle each of the distinct and often unforgiving environments of air, sea, land and space. Secondly, the system must be compact and lightweight, allowing the user full freedom of movement and maximum comfort while wearing the device. Lastly, the system must be accurate enough to handle critical operations, whether the user is tracking an enemy target or capturing a free satellite in space. The review presented below will outline the system level drivers, application specific drivers, basic principles of inertial navigation system (INS) and GPS, the advantages to GPS/INS integration and finally, the recommendations for the TLS navigation package.

2.3.1 System Level Drivers

The objective of this overview is to arrive at a design solution for a self-contained, human-mounted navigation package to drive the TLS for both air and space (EVA) applications. As a result, the system is required to produce an accurate six degree-of-freedom, real-time navigation solution. The unit should be compact, lightweight, robust, reliable, versatile and affordable. In addition, the unit should have a low-power requirement (that can be satisfied without the use of external power sources) and be able to be integrated easily with the existing vibrotactile system.

2.3.2 Application Level Drivers

The navigation package would have to be easily integrated into the EVA space suit with as few modifications made to the suit as possible. Another requirement is to withstand the harsh space environment, namely vacuum, radiation and extreme temperature ranges. For a helicopter hovering scenario (discussed in Appendix D), a non-obstructing unit is essential; note that the size and weight limit of the unit is defined by this application. The unit may be attached to the backpack of the EVA suit and therefore be unobtrusive to the astronaut, whereas the pilot must wear the unit directly on the body, maintaining maneuverability, agility and acuity. In addition to the physical limitations associated with each application, precise and reliable attitude determination, and position, velocity and time (PVT) solutions are also required for both applications. The two navigation systems considered were INS and GPS. The following sections introduce these systems and state their advantages and disadvantages.

2.3.4 Inertial Navigation

Inertial navigation relies on accelerometers and gyroscopes (gyros) for three-dimensional attitude, position and velocity determination. Three accelerometers placed in an orthogonal triad on a platform measure specific forces, while gyros measure the angular deviations and rates of the platform with respect to a fixed reference frame. Gyros can be implemented in two configurations, gimballed or gimballess (strap-down). Ring laser gyros (RLGs) and fiber optic gyros (FOGs) are two examples of state-of-the-art components in strap-down systems. While strap-down systems require more computation and have less calibration flexibility, they are small (on the order of three cubic inches), have few or no moving parts, and cost considerably less than conventional spinning mass gyros [Weiss, 1996]. Whereas the electronics to support conventional gyros and accelerometers are cumbersome, recent advances have been made in the miniaturization of RLGs. Benefits of INS include extremely accurate attitude determination with high output rates (approximately 50-100Hz iteration rates, even in the presence of large dynamic disturbances) and because the system is self-contained, immunity to outages [May, 1993].

INS errors can be caused by the interaction of vehicle inertial motion, instrument noise, instrument and platform misalignments, initial position and velocity errors and gravitational disturbances. These errors may grow unbounded, however, they do tend to oscillate slowly and with a fairly predictable frequency, allowing for possible mitigation. Platform alignment is accomplished in part, through gyrocompassing, during which the INS seeks to level the orientation of the platform while simultaneously nulling the difference between the sensed and computed easterly component of the Earth's rotation. Misalignments made during this process accumulate throughout accelerometer outputs, resulting in a degraded navigation solution [May, 1993].

Due to the lack of specific force measurements in space (unless the astronaut is actively accelerating), inertial navigation systems are unfortunately not as effective in low-G environments. Thrusting may be done to calibrate the INS, however, during periods when the astronaut is not accelerating, the accelerometers will output no more than the accelerometer bias. While the

INS will not maintain an accurate position or velocity fix in such situations, its attitude solution can be held accurately.

2.3.5 Global Positioning System

The Global Postioning System provides a precise position, velocity and time solution based on psuedorange measurements (sampled at ≈ 1 Hz) made from the 24 GPS satellites orbiting the earth, to the user's receiver on the ground. Ranges are measured to at least four satellites in view simultaneously, by correlating the satellite signal with the user-generated replica signal and comparing the received phase with the users internal clock [Parkinson, 1994]. GPS satellites broadcast a ranging signal at two frequencies, L_1 (1575.42 MHz) and L_2 (1227.6 MHz). There are two modulations on the higher frequency, but only one modulation (that is protected) on the lower frequency. The first modulation is called clear acquisition or C/A code, broadcast at a rate of 1.023 MHz. C/A code is unencrypted (available to all users) and users of this signal employ the standard positioning service (SPS). The military may also degrade the C/A code (by desynchronizing the satellite clock) by as much as 20 m in range and 50 m in horizontal position (selective availability). The second modulation is called Precise, or P code. Broadcast at 10.23 Mhz, its larger bandwidth allows fore more precise solutions (known as the precise positioning service or PPS). The military has encrypted this signal (called Y code) so that is only available to authorized users [Parkinson, 1994]. While, in general, GPS hardware is compact, encryption electronics add weight and volume for P/Y code users.

GPS is also capable of measuring the relative positions of multiple antennas mounted to vehicles or platforms at real-time output rates of up to 10Hz, resulting in accurate attitude solutions. The attitude solution utilizes the sub-centimeter precision of the carrier phase signal from the GPS satellites to measure the relative range between a pair of antennas; three antennas will give the full three-axis attitude solution [Cohen & Parkinson, 1993].

Differential GPS (DGPS) employs a ground station whose position is known precisely. Because the absolute position of the ground station is known, the biases (or differential corrections) in the measurements can be determined and sent to all receivers in the area. DGPS can increase the accuracy of the GPS solution by removing common (correlated) errors by as much as an order of magnitude for civilian C/A code users. One way to smooth the navigation solution is through the use of a Kalman filter. Kalman filters provide optimal estimates of the PVT solution using an algorithm based on noise statistics and measurements, as well as utilizing a dynamic model of the receiver platform motion [Kaplan, 1996].

Although GPS is subject to outages that may significantly degrade the PVT solution, it is practically immune to drift, and can provide velocity solutions accurate to 0.02 m/s for PPS receivers. While Kalman filters can help to smooth the solution during GPS outages and with fewer than four satellites in view, accuracy may also be degraded by atmospheric interference, radio frequency interference (RFI), jamming, antenna shading and multipath effects. Multipath is one of the largest sources of GPS receiver measurement error, and occurs when a satellite signal arrives via multiple paths due to reflections off of the Earth's surface and other objects (i.e., buildings and vehicles) [Kaplan, 1996].

Unfortunately, many of these error sources still exist in space, particularly multipath errors, due to the high concentration of objects (i.e., the orbiter docked with the ISS) in a small region where the signals are being transmitted. The following section describes how some of these errors can be mitigated through the integration of GPS and INS, and section 2.3.7, Recommendations for EVA Navigation, presents a design solution for a space based application.

2.3.6 Integrating GPS/INS

Integrating GPS and INS can provide a more robust and accurate navigation solution than is available with stand-alone sensors. Accuracy may be maintained during GPS outages with INS aiding. INS provides navigation solutions during outages, as well as position aiding to the GPS to assist in re-acquiring satellite signals after loss of signal lock. INS is consistently aided by GPS when both systems are functional, for the INS errors will be bounded by updates from the GPS solution. Because of the higher update rate of INS, position changes can be precisely measured between GPS updates. Finally, INS aided GPS can provide solutions over a wider range of vehicle dynamics and in the presence of RF interference; jamming margins can increase by at least 15 dB for pseudorange measurements. Each 6 dB increase in jamming margin represents halving of the distance at which a jammer of a given power could disable availability of GPS [May, 1993].

In the reverse situation, GPS will assist INS in calibration through the Kalman filter, by estimating the biases in the INS at power-on using GPS velocity data. The Kalman filter in this integrated system will also serve to weight the INS and GPS solutions to produce the optimal error variances based on statistical knowledge of the system errors and dynamics, as discussed previously. The GPS can also aid the INS alignment by providing velocity residuals. Sensing INS alignment errors from velocity residuals rather than from position residuals (as in gyrocompassing) eliminates the delay incurred to integrate a velocity error to a position error of detectable magnitude [Greenspan, 1996].

2.3.6.1 Modes of Integration

There are two methods of integrating GPS and INS, called loosely-coupled, and tightly-coupled. Figure 2.3.1a shows one example of a loosely coupled system; it takes the Δq's (angle rates) and Δv's (accelerations) from the inertial measurement unit (IMU) to one navigation processor, and r (the pseudo-range data) from the channel processor into the GPS receiver processor. It also has a feed forward loop from the navigation processor and two separate filters, allowing for instabilities from mutual feedback and resulting in a non-robust system. Here, the complete navigation solution may contain unmodeled errors from the GPS receiver processor. Figure 2.3.1b shows a tightly coupled system. The Kalman filter in the GPS has been eliminated and the pseudo-range and pseudo-range-rate data is fed directly into the navigation processor.

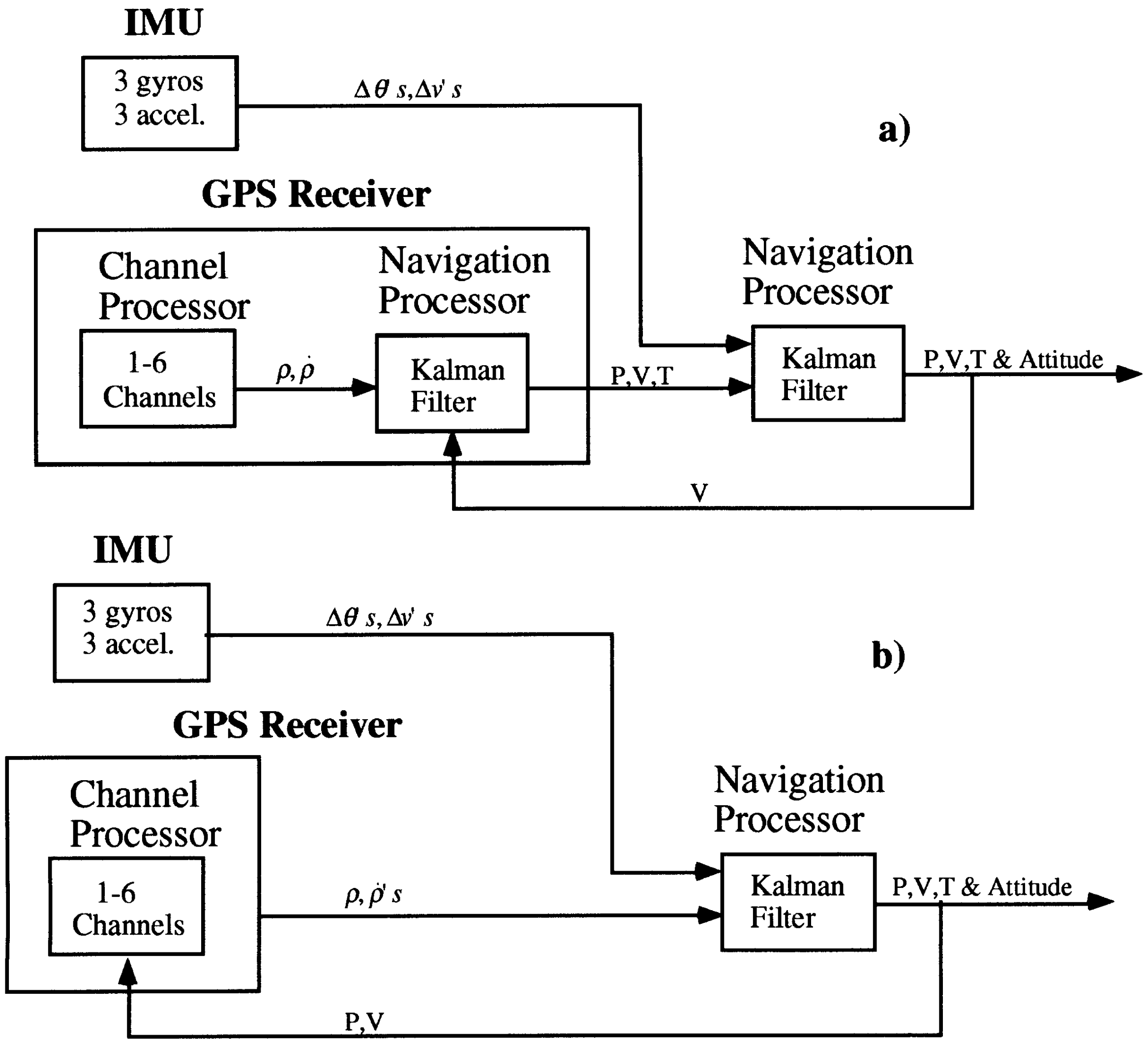


Figure 2.3.1 Integrated GPS/INS configurations: a) a loosely integrated system, b) a tightly integrated system [Kaplan, 1996].

Figure 2.3.2 shows the functional block diagram of the tightly coupled system. Notice that the Kalman filter estimates the state errors (rather than the state itself) and subsequently uses that estimate to correct the navigation equation outputs.

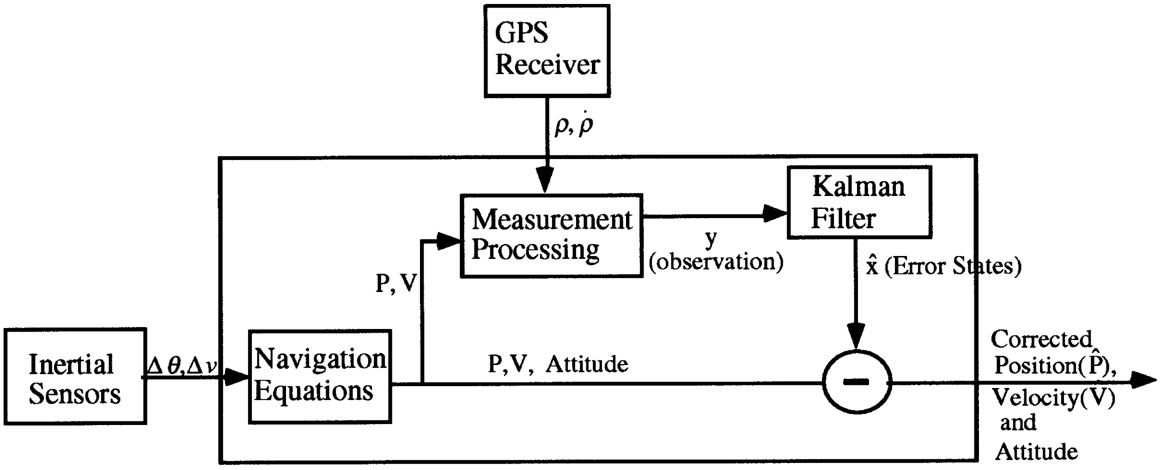


Figure 2.3.2. Functional Block Diagram of a tightly coupled GPS/INS system [Kaplan, 1996].

The tightly coupled system has the GPS and INS embedded in a single unit minimizing data bus traffic, latency, and protecting encrypted code data transfers. In addition, integrated systems in this configuration are already equipped for DGPS. Cohen reports, "the state-of-the-art in attitude receivers is small (1300 cc), light (~1.5 Kg), and low power (~3.5 W), so that one can be carried on just about any spacecraft [Cohen, 1995]." Therefore for this research effort, a tightly-coupled integrated GPS/INS package is recommended. In the following section, this integrated system will be considered in the two applications of an astronaut conducting an EVA and a pilot in a hovering helicopter.

2.3.7 Recommendations for EVA Navigation

In space, where the accelerometers of the INS are not functioning at their full capability, the local relative position, velocity and attitude solution will be provided by GPS. Research is currently being conducted to evaluate the accuracy of an absolute, unaided GPS attitude solution in space [Mitchell *et al.*, 1996]. One concern that arises regarding absolute position and attitude determination of an astronaut conducting an EVA, is the placement of the antennas. As mentioned previously, three antennas are required for a three-dimensional GPS attitude solution, however these antennas must be placed in a rigid location and at fixed distances apart. On average, two antennas placed one meter apart will have a standard deviation of one milliradian. It is simply not feasible to place a rigid triad of antennas within the confines of the EVA suit. Results have shown that even with ample space available, there are still inaccuracies in the unaided absolute solution beyond the limits required for this research. However, this problem can be virtually erased by using relative GPS with INS aiding. Relative GPS measurements are necessary for such applications as station keeping, rendezvous and capture, and automated docking. This relative range method requires a GPS antenna and receiver on both the astronaut and target, and can keep errors in position to within centimeters, errors in velocity to within tenths of centimeters per second, and attitude errors within 10 milliradians. The astronaut's antenna can easily be attached to her helmet or backpack (where the navigation unit will be located). Determining the distance between the astronaut and her target (i.e., ISS module, Shuttle or free satellite) requites a GPS receiver on the same. GPS has already been flown on several Shuttle flights, and by 1998 the Shuttle is expected to use GPS for guidance and navigation in almost all phases of its missions [Kaplan, 1996]. On a free satellite, for example, where a GPS receiver may not be available, laser range finding may be used, or else the precise position of the satellite in its orbit may be fed to the GPS/INS navigation processor.

During GPS outages, the INS will successfully hold the attitude solution with a maximum drift rate of one degree per hour. Bandwidth on an existing communications/data link is needed to transmit the signals between the two antennas. Aligning to a fixed coordinate frame (discussed further in the following section) can be accomplished in flight depending on the mission specifics. As an example, the Shuttle remote manipulator system (RMS) can be used to point the astronaut in the desired orientation and provide a stable base throughout the alignment process. In terms of power consumption, it may be feasible to use solar panels if it is necessary to charge batteries in the days before the EVA, and in-between EVA's.

While atmospheric effects do not contribute large errors in the space environment, multipath errors are of great concern in situations where structures in close proximity can reflect signals off of one another. While these errors can be estimated to some extent in the Kalman filter, they are generally very difficult to predict and vary greatly from mission to mission. Finally, the GPS receiver and processor must be configured to handle the larger number of bits required to solve for the increased Doppler shifts resulting from higher velocities experienced in space than on Earth. Therefore an autonomous, wearable navigation unit can be achieved with a INS aided GPS unit and DGPS, and used with either the Space Shuttle, or the ISS.

3. PILOT STUDY

This chapter presents the methods, data analysis and results of a pilot study conducted prior to the ISS simulation experiment. The results from this study are significant in that they drive the methodology of the ISS experiment.

3.1 Directional Vector Resolution Study

The purpose of conducting a pilot study was twofold: 1) to determine the utility of a vibrotactile stimulus to display information to the user, and 2) to determine if six tactors was sufficient to convey directional information to the user. In essence, the study was able to quantify the ability of subjects to resolve one, two and three vibrotactile stimuli applied to the torso, into a directional vector in space. An auditory control was chosen in order to compare the vibrotactile stimulus with another non-visual stimulus. As discussed previously, in the case of the Shuttle where the EVA crew is within view of the cargo bay, an IVA crew member in the cabin may be able to give verbal directions to another astronaut. A crew member inside the space station may not be able to accomplish the same, therefore it is useful to compare the two methods. The TLS configuration in this case contained six vibrotactors, the minimum number necessary to communicate a 3-D sphere around the subject (centered at the torso).

3.2 Experimental Set-up

Four female volunteer subjects participated in the pilot study (ranging in age from 23 to 26), and began by sitting in an ergonomic chair to simulate a 'neutral body' posture. The chair was situated in front of a Silicon Graphics (SGI) Indigo 2 workstation that displayed a 3-D 'sphere of targets', with each target representing one of 26 possible directions in space (see Figure 3.2.1), the center of the sphere represents the center of the subjects' torso.

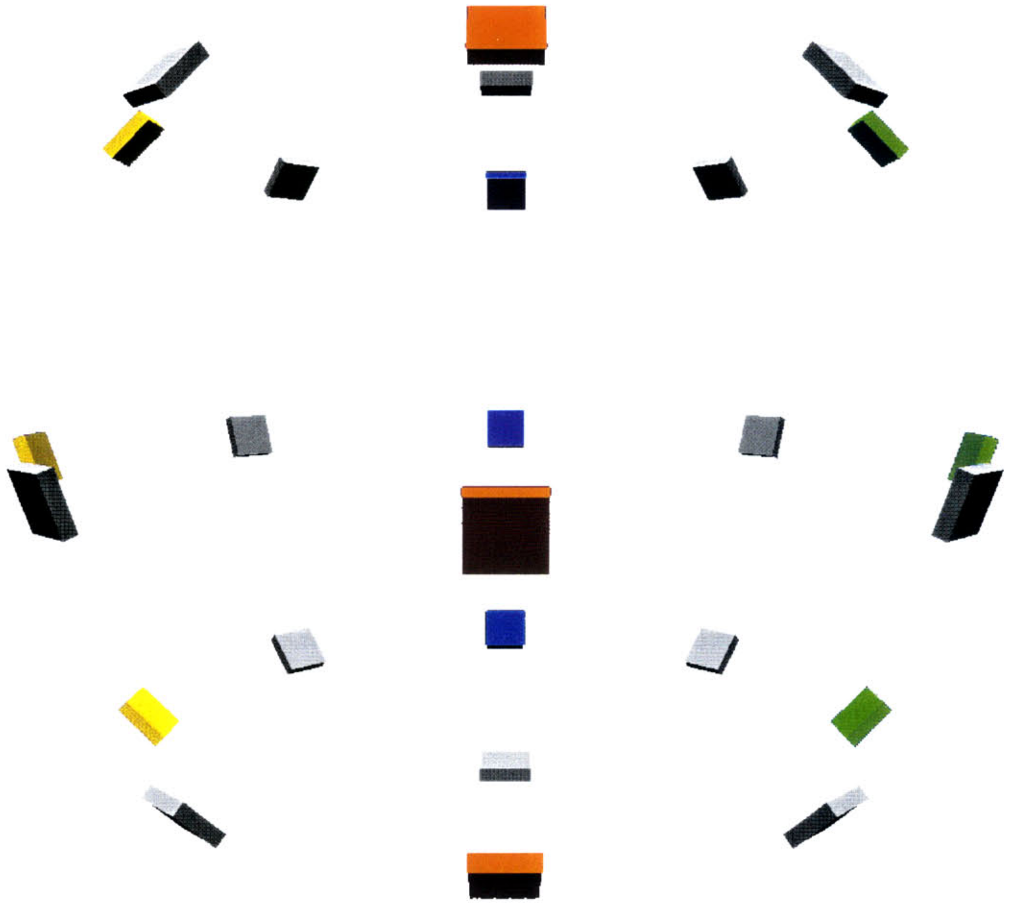


Figure 3.2.1 Sphere of targets used for pilot study.

Notice that the targets are color coded to aid recognition. Targets directly in front, back, right or left (regardless of the height above the "horizon") are colored, while the diagonal targets remain gray. In addition, all front targets are similarly colored, likewise for the back, right and left groups. The SGI was also responsible for data collection and recorded variables such as subject, trial, stimuli number and reaction time. The torso was selected as the region to present the vibrotactile stimulus, as well as the neck and buttocks. An advantage of the torso is that it is the largest, most stationary, and intuitive part of the body upon which to map a coordinate frame. The TLS is presenting information about another astronaut's position with respect to your center of mass, therefore it requires little mental transformation to associate the origin of a coordinate system with the center of one's torso. Tactors (approximately 1/2" in diameter and 1/4" thick) were arranged on the subject as shown in Figure 3.2.2, with each tactor corresponding to one of the directions up, down, front, back, left and right.

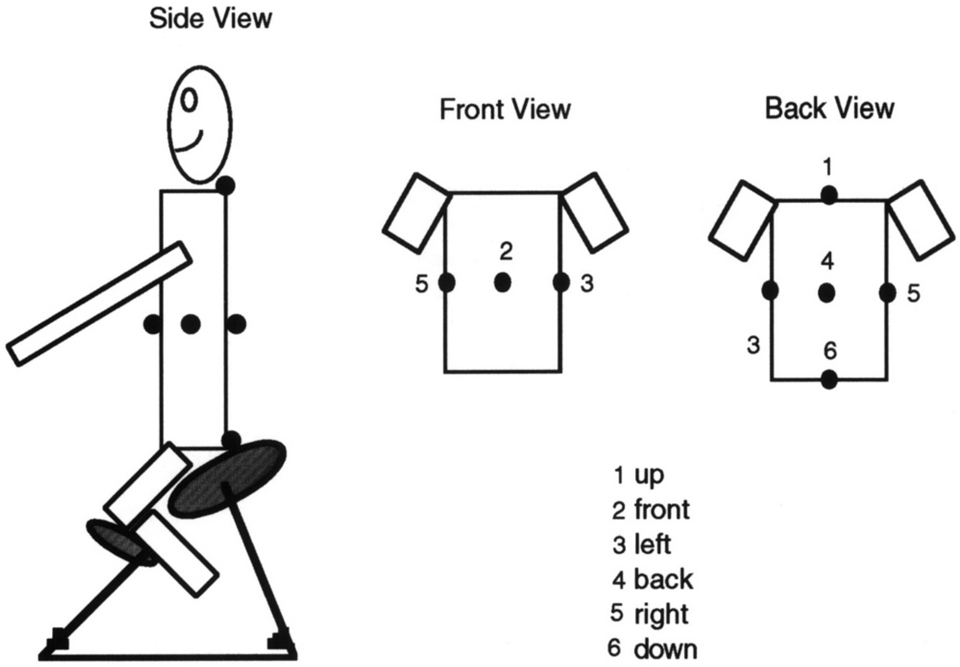


Figure 3.2.2 Position of vibrotactors on body.

Tactors were either attached to a canvas belt that was secured with velcro, or tied in place. Placing the tactors around the torso in this fashion exploits some of the characteristics of the skin as discussed in the previous chapter. While the back is one of the least sensitive regions on the body, recall that point localization thresholds did not significantly vary around the torso, suggesting that a subject should have no more difficulty detecting a localized stimulus on the back than on the chest. In addition, the phantom sensation indicates that tactile stimuli presented simultaneously in the front and on the right, for example, would result in a sensation of a stimulus midway between the two.

In addition to the Silicon Graphics workstation, a power Macintosh 8100/80 was employed for tactor control. Tactors were manually activated and deactivated by the experimenter via a LabView program (National Instruments, Austin, TX). The numbers indicated in Figure 3.2.2 represent tactor activation buttons (see Appendix A for LabView control panel and program). The LabView MIO-16 DAQ card outputs the on/off information to a controller box, which in turn, activates the tactors. The data acquisition card has eight digital I/O lines; seven control tactors and one acting as the clocking signal for the flip flop in the controller box. For reasons of symmetry (to equally partition the regions of space denoted by any given tactor combination), six tactors were chosen to convey position information to the subject, out of the possible seven. Notice that the neck and buttocks have been chosen in this design to represent up and down. The original design was to place the 'up' tactors over the shoulders, and the 'down' tactors under the thighs, however, with the six tactor limit, the design would be forced to favor either the right or left side. As a result, the neck and buttocks were chosen (notice that in this posture, the buttocks most nearly represents down, with respect to gravity). As mentioned previously, the SGI recorded two data variables: reaction time and selected target direction. Reaction time was measured from the onset of the tactile or auditory stimulus to the time when the subject selected (clicked on) a target. A TCPIP (Transmission Control Protocol/Internet Protocol) connection was established between the computers, so that the SGI graphics program began timing the subject when the tactor stimulus had been initiated via the Macintosh[1]. A block diagram of the system is shown in Figure 3.2.3.

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[1] All SGI programming was provided by Research Assistant David Rahn from the Man-Vehicle Laboratoy at MIT.

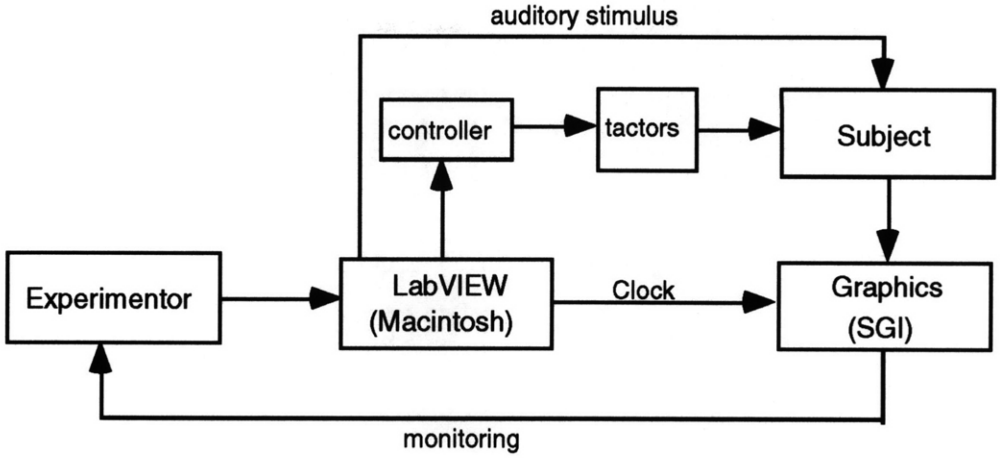

Figure 3.2.3 Block diagram of pilot study system.

3.3 Vector Resolution Protocol

Subjects were told that the goal of the trials was to click (using the computer mouse as the input device) on the perceived direction of a stimulus in response to either a control (auditory) or experimental (tactile) cue. Auditory commands were given with combinations of the aforementioned directional words. For example, saying "up and right" would signal forty-five degrees horizontally once the subject resolved the two vectors 'up' and 'right' (see Figure 3.3.1).

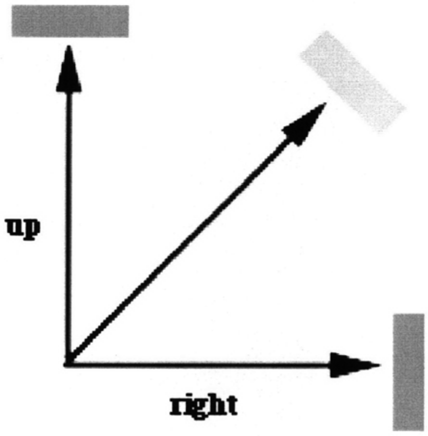

Figure 3.3.1 Schematic of vector stimulus resolution.

Once either the auditory or tactile cue had been given and the subject had discerned the direction of the position vector, she was to click on the appropriate square and return the cursor to its starting position at the center of the sphere as quickly as possible. Each session consisted of 26 stimuli (one for each possible direction) presented in a random order. Each stimulus could indicate as few as one direction (one tactor, or 'left' for example), and at most three (i.e., up, left, back or three tactors). Two sessions were conducted with tactile cues and two with auditory cues, for a total of four conditions (also presented in random order). In addition, a practice session was run to acclimate the subjects to the feel of the vector manipulation, vibrotactors and graphics. Data from the practice sessions were not used in the statistical analysis. Although the distances to different targets varies, each stimulus is presented in every session to enable comparisons as to the nature of the stimuli.

3.4 Data Analysis

The following section describes the statistical analysis performed on the pilot study data (see Appendix C), with results discussed in section 3.5. Data were divided into four categories labeled T1, T2, C1, C2, for Tactor trial 1, Tactor trial 2, Control trial 1 and Control trial 2, respectively. While the order of sessions was random, they have been organized and presented as stated above. Within each session, incorrect responses (directions) were denoted for data analysis. Modality refers to either control or tactor, while repetition denotes either the first or second (session). For each modality and repetition, the mean, variance and standard deviation of the reaction times were calculated. Finally, the 26 stimuli have been grouped into three categories, or levels of difficulty, according to the number of tactors activated to convey that direction (either 1, 2 or 3).

A fully factored Analysis of Variance (ANOVA) was performed to compare the variance of the difference in reaction times *within* subjects, versus *across* subjects. Paired t-tests were performed between the modalities and the repetitions, that is to say, between T1 and T2, C1 and C2, T1 and C1, and T2 and C2 (results are shown in Table 3.5.1). This calculation will give some insight into the utility of a display using the unexploited tactile modality versus the more colloquial auditory modality. Another important statistic, is to observe how the reaction time varies with the stimulus. As mentioned previously, stimuli varied from one to three directions. Difficulty encountered in resolving multiple stimuli (directions) could suggest the need to a increase the number of vibrotactors, thereby reducing the number of directions to be resolved in a given trial. The last two results deal with the number of incorrect responses given; the correlation between the number of incorrect responses given for a particular stimuli, over all subjects and sessions, and the number of incorrect responses given in each session for each subject.

3.5 Results and Discussion

Reaction times within and across subjects proved to be highly significant (p=0.0001), suggesting that each subject performed quite individually. However, when the ANOVA was repeated without subject D, the variance was not significant. This suggests that subject D had a very different strategy for target selection from the other subjects. It has been suggested that subjects A, B, and C chose to hastily move the cursor in the general direction of the stimuli, then refined the direction while approaching the target, whereas subject D discerned the correct direction before moving the cursor. This can be confirmed, for while subject D had the largest reaction times, she had the highest accuracy. In fact, subject D made 4 times fewer mistakes than other subjects. As a result, statistics have been performed in two subject groups; subjects A, B and C together, and subject D alone. Reaction times were, overall, higher for the tactile stimulus than for the control (auditory) stimulus. Both groups showed a significant difference in reactions times (p=0.0204; p<.0001) across modality. This result is not entirely unanticipated due to the unfamiliarity of subjects with tactile sensation, in addition to which, the subjects conducted only one practice session prior to collecting data. While it is assumed that astronauts will train with the TLS, thereby overcoming any learning curve effects that are present with this new device, the number of practice runs required to train a subject will most likely vary from person to person. Unfamiliarity with the graphic representation was lessened as a result of the practice run, however, it still remained a factor throughout the experiments. Subjects complained of selecting the wrong target when there were two in close proximity, and of confusing back targets with front targets.

Table 3.5.1 shows the results of the modality and repetition comparisons.

Table 3.5.1 Pilot study contrast results.

SUBJECTS	T1 vs. T2	C1 vs. C2	T1 vs. C1	T2 vs. C2
A, B & C	p=0.995	p=0.895	p=0.149	p=0.236
D	p<0.001	p=0.942	p<0.001	p=0.046

With the exception of subject D, there was no significant difference between successive tactor and control trials. This suggests that there was not a great deal of improvement between the first and second run of either condition. Subject D, however, showed a significant improvement in reaction time from the first to the second tactor session. It would be necessary to conduct several more sessions and observe if there was a steady decline in the mean reaction time, so that the learning curve could be assessed. It would also be interesting to note if performance is degraded when there is a significant time between uses of the tactile aid, or whether the skill is not reduced over time. This could be accomplished be simply testing subjects with varying numbers of days between experimental sessions.

Figure 3.5.1 shows the reaction time versus stimulus for each subject (all sessions are shown). Not surprisingly, reaction time is highly correlated with the nature of the stimulus, as denoted by the rising slope of each of the plots. It seems intuitive that the greater the number of vectors to be resolved, the greater the time required to determine and select that direction.

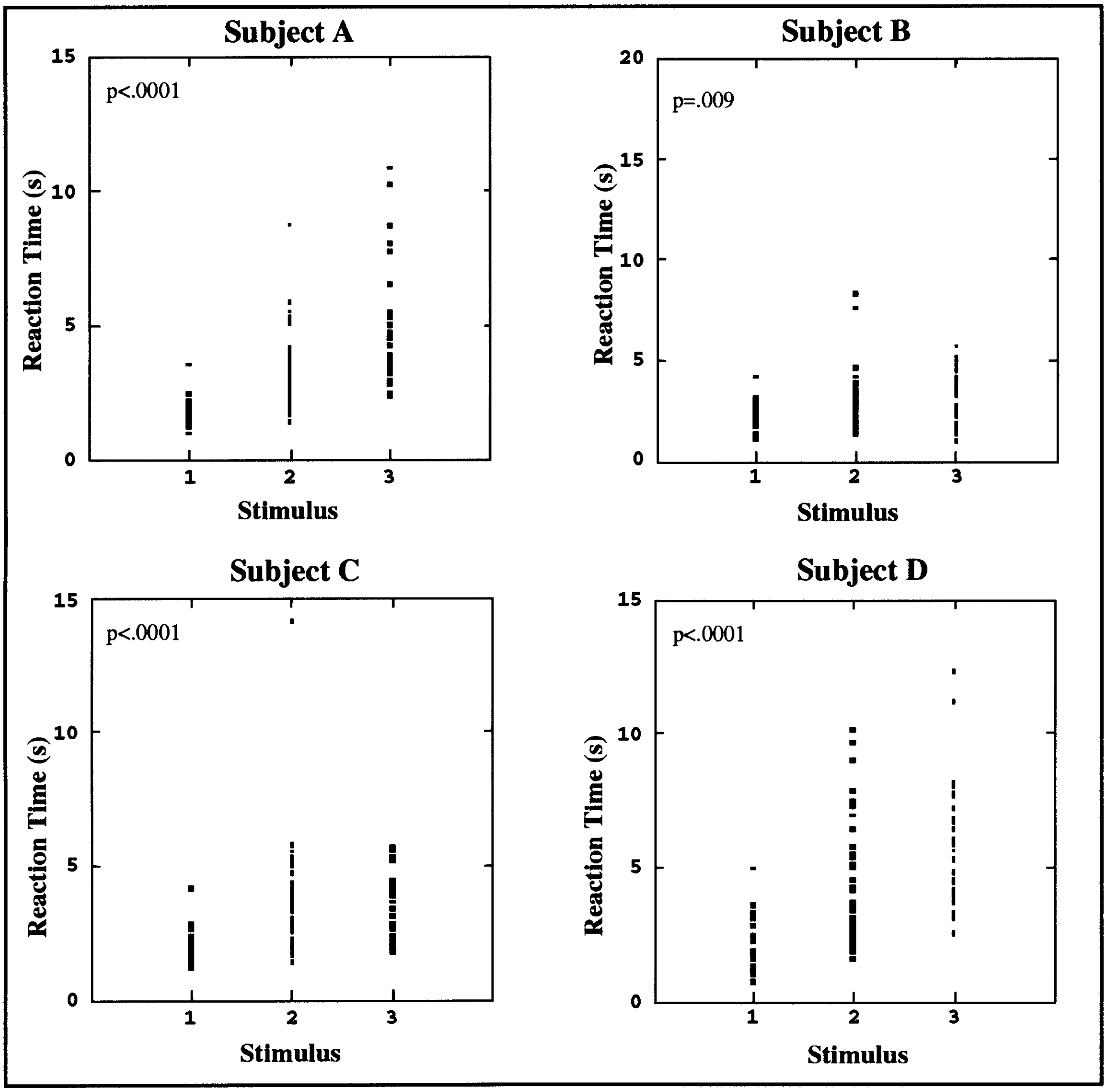

Figure 3.5.1 Reaction time versus stimulus for each subject.

By group, as well as individually, reaction times were found to be significantly higher as the number of tactile stimuli increased (group 1:

p<.0001, group 2: p<.0001). The data suggest that requiring the subject to resolve more than two vectors (tactile stimuli) simultaneously results in time penalties. Figure 3.5.2 shows the correlation between the number of incorrect responses given for a particular stimulus, over all subjects and sessions.

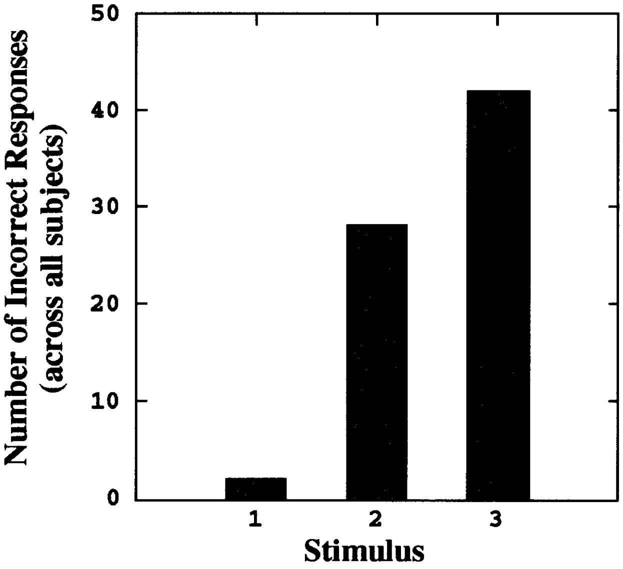

Figure 3.5.2 Number of incorrect responses versus stimulus for all subjects.

As expected, the greatest number of incorrect responses were given when subjects had to resolve three vectors to determine position. Figure 3.5.3 shows the number of incorrect responses given in each session for each subject.

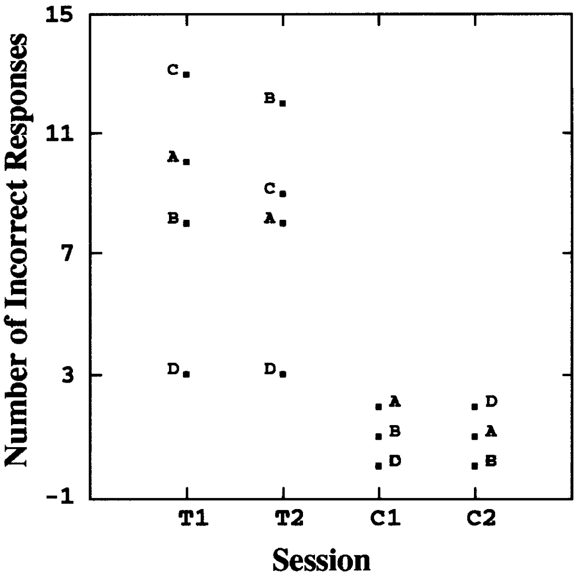

Figure 3.5.3 Number of incorrect responses versus session for all subjects.

This plot clearly demonstrates that more errors were made in interpreting the tactor signals, than the auditory signals. In addition to the problems of unfamiliarity and lack of training, there may also exist problems concerning sensitivity which would also explain this trend. As discussed previously, the back is one of the least sensitive regions of the body. Subjects complained that it was difficult to feel the back tactor, particularly when it was presented in addition to two other tactors. As a result, the tactor often went unnoticed and the response took into account only two of the three stimuli.

The following chapter will outline the details of the ISS EVA experiment. The design and protocol selected attempted to address some of the questions raised by the pilot study. For example, the effect of learning, performance over time, and resolving multiple directions in space on reaction times and task performance.

4. METHODS

4.1 ISS EVA Simulation Experiment

This experiment tests the effectiveness of the TLS in one of many possible ISS EVA scenarios, that of quickly traveling to an astronaut at another location. Incorporating lessons learned from the pilot study, the TLS configuration is described and the experimental set-up and protocol presented. Finally, the data analysis methods will be outlined.

4.1.1 ISS Task Scenario

The scenario chosen for this study follows: two astronauts are conducting an EVA at different parts of the ISS. Your partner has a problem and you need to get to her as quickly as possible. The TLS, when activated, will give you a reading of the position vector to your partner. When the TLS is not activated, you will be told where on the ISS your partner is located. At the NASA workshop on Technology for Space Station Evolution, a similar scenario was discussed, that of "retrieving an incapacitated EVA crewmember who is detached from the Space Station [Willshire, 1990]". The following section describes the hardware, software and input device used for this task.

4.1.2 TLS Configuration

The tactors were placed in the same locations as that of the pilot study; one on the neck and buttocks, and four around the chest. However, in light of the results discussed in the previous chapter and subjective comments made by the pilot study participants, changes in the method of tactor placement were implemented. Of the comments received regarding the experiment, each subject suggested delivering a more discrete tactile signal to avoid ambiguous information. Rather than placing multiple tactors on a belt, each tactor was taped directly to the skin using athletic tape to ensure a close connection to the skin and a localized stimulus. In addition, the tactor located on the chest was placed closer to the breast plate to increase the vibration and enhance the vibrotactile sensation. Before each session, the tactors were activated in turn and simultaneously, then adjusted per the subject's perception of the maximum sensation both in strength and localization.

4.1.3 Experimental Set-up

Subjects were seated in an ergonomic chair in front of the SGI workstation. The simplified model of the ISS (shown in Figures 4.1.1), was drawn using the SGI software program Cosmo (Mountain View, CA)[2].

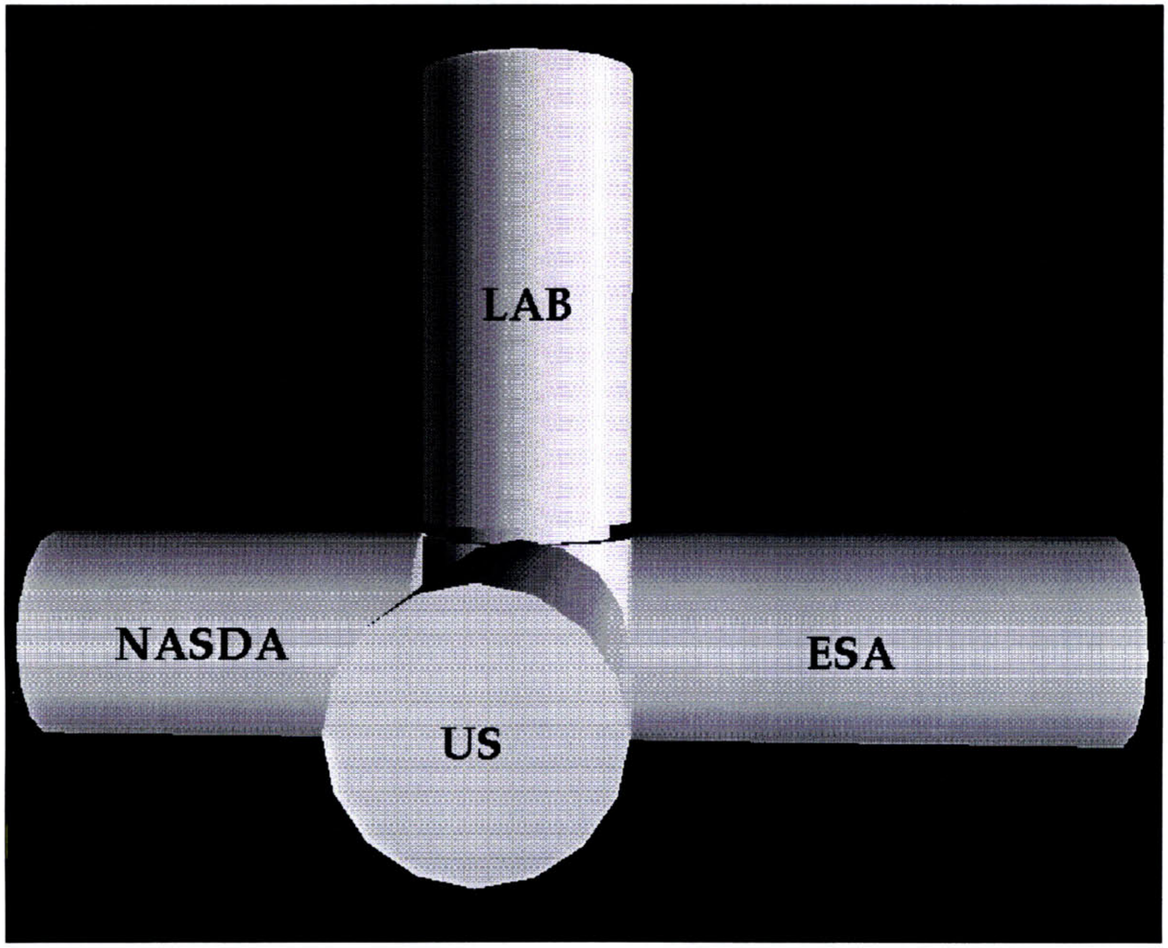

Figure 4.1.1 Simplified ISS model. Labels were not used during any phase of the experiment.

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[2] Programming of the COSMO model was provided by Qun Liang.

It is representative of four of the modules on the ISS - the US and US Lab modules, the NASDA module, and the European Space Agency module. The astronaut and EVA suit model, shown in Figure 4.1.2 is from the Johnson Space Center IGOAL laboratory.

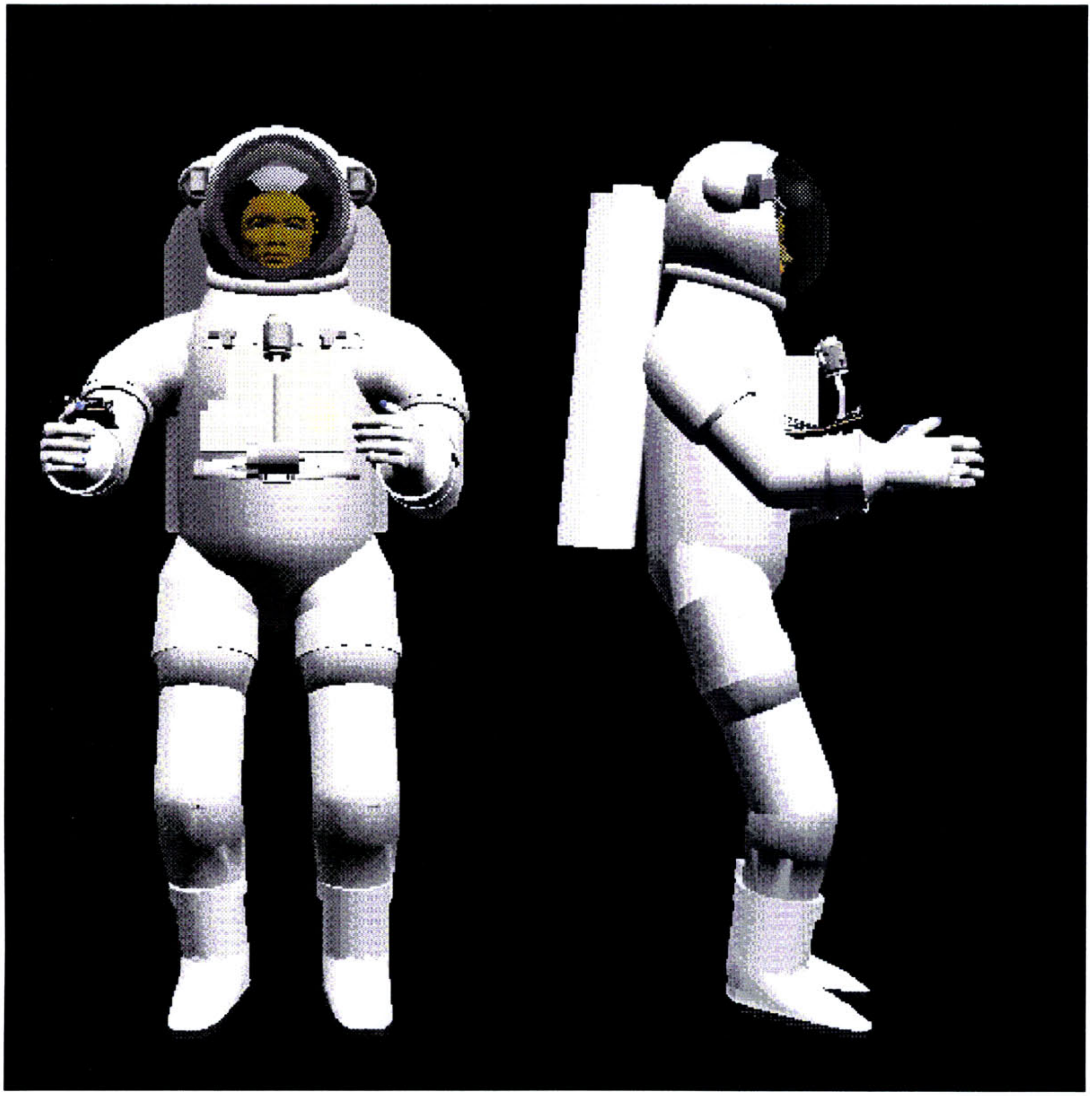


Figure 4.1.2 Astronaut and EVA suit model.

To give the subject the impression of being inside an EVA suit looking out on the ISS, the astronaut model was incorporated into the Multigen II (San Jose, CA) software package to adjust the model such that the subject could see the helmet and arms of their own suit (see Figure 4.1.3).

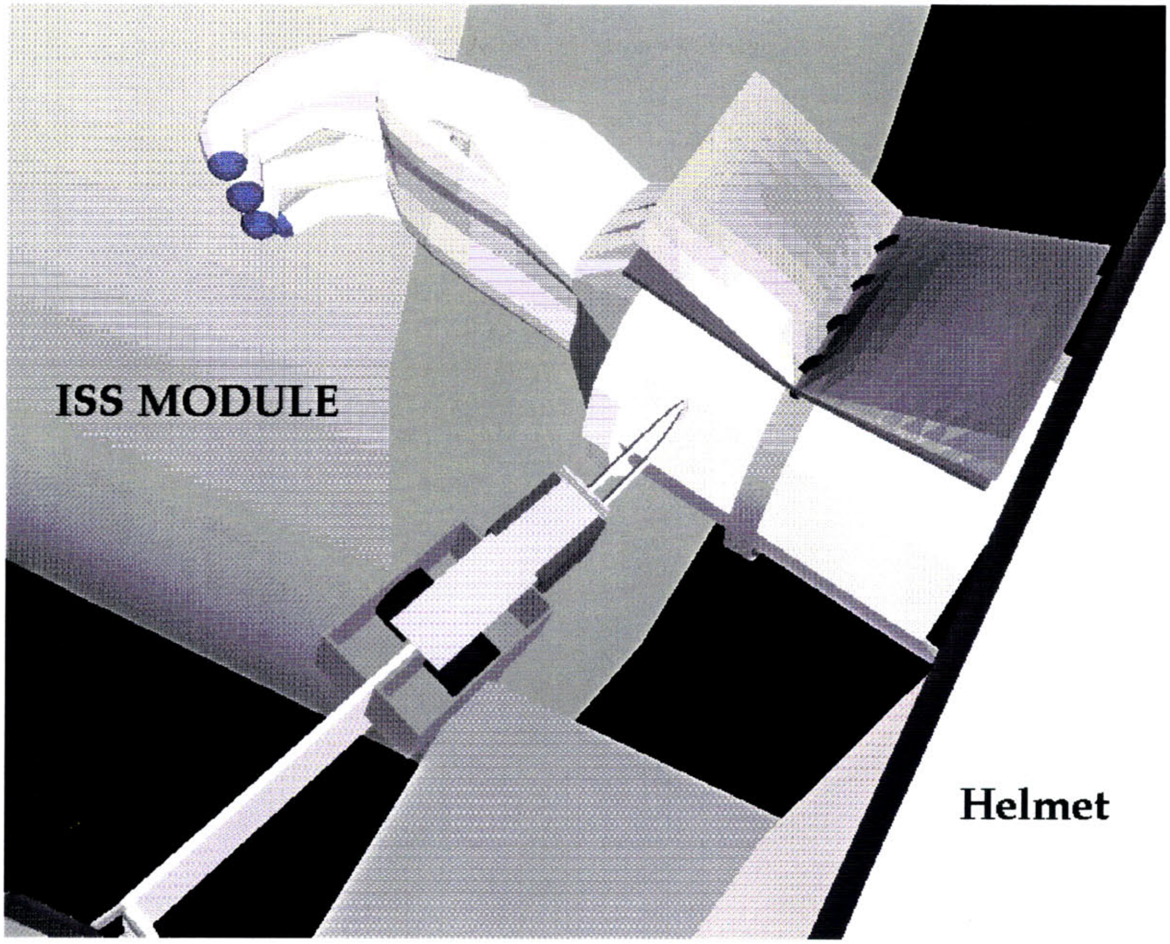


Figure 4.1.3 Subject's view from inside the EVA suit. One view looking down at the EVA suit and helmet rim. Subject's changed position of the head within the helmet and were able to look around the scene using the mouse.

Paradigm Simulation's (Dallas, TX) Vega software with Lynx was the program used to compile the elements of the simulation. The simulation consists of the ISS model and the two models of astronauts in EVA spacesuits, one for the target and one for the subject as seen above. Subjects move throughout the ISS simulation graphics using the Spacetec IMC Spaceball 3003 (Lowell, MA) a six degree of freedom (d.o.f.) input device shown in Figure 4.1.4. The dynamics controlling the Spaceball include little damping to give the subjects ample feeling of moving through space, while allowing the motions to be controlled.

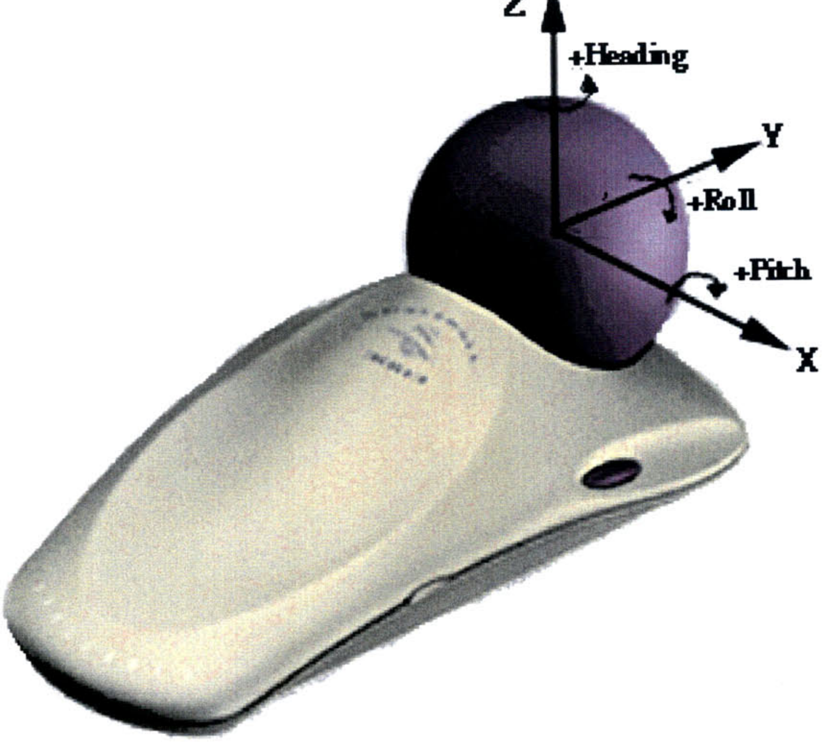


Figure 4.1.4 Spaceball 3003 input device with translation and rotation control directions indicated.

The tactor activation procedure was automated using LabView (see Appendix A). The SGI sends the 8100/80 Power Macintosh LabView program the position and attitude (pitch, roll and yaw) of the subject and of the target astronaut in 'world coordinates', with the origin at the center of the ISS model. The two vectors are then subtracted to give the vector between the subject and the target. A coordinate transform converts this vector to the subject's body coordinate frame, thereby producing the directional vector from the center of mass of the subject, to the target astronaut. The direction cosine transformation employed for this calculation assumes the body axes, defined as $+X_{body}$ through the chest of the subject, $+Y_{body}$ out the right side and $+Z_{body}$ down through the feet (see Figures 4.1.5 and 4.1.6).

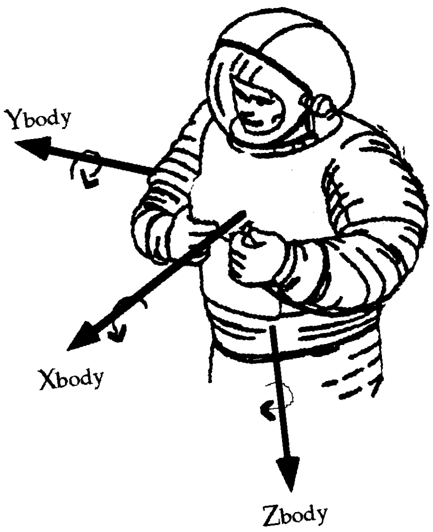
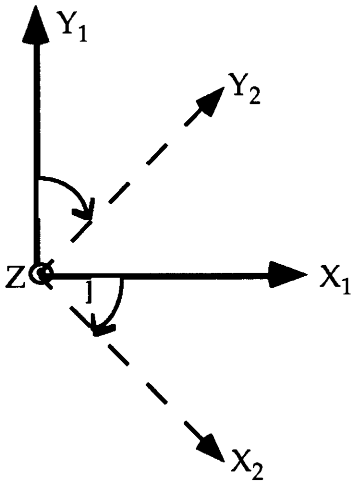


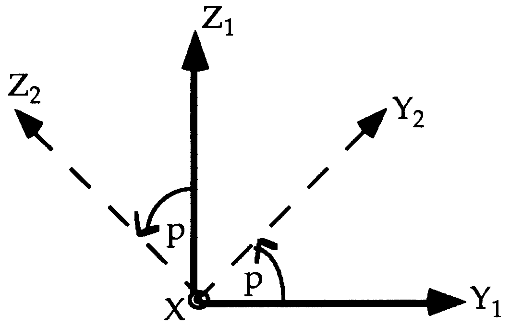
Figure 4.1.5. Astronaut body axes.

Heading (h) Transformation



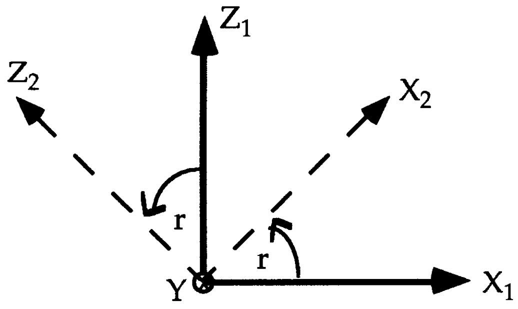
$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \underbrace{\begin{bmatrix} \cos(h) & \sin(h) & 0 \\ -\sin(h) & \cos(h) & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{H} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}$$

Pitch (p) Transformation



$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(p) & \sin(p) \\ 0 & -\sin(p) & \cos(p) \end{bmatrix}}_{P} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}$$

Roll (r) Transformation



$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \underbrace{\begin{bmatrix} \cos(r) & 0 & -\sin(r) \\ 0 & 1 & 0 \\ \sin(r) & 0 & \cos(r) \end{bmatrix}}_{R} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}$$

$$R_{body} = (R^*(P^*(H^*R_{nav})))$$

Figure 4.1.6 Direction cosine transformation.

Finally, the angles ϕ and θ are then calculated from the vector output from this transformation to give the vector from the subject to the target astronaut in spherical coordinates. Given that each of the 26 directions in space defined earlier for the pilot study correspond to a tactor firing pattern, defining square projections around each allows determination of the appropriate set of tactors to fire for a given pair of angles (see Figure 4.1.7).

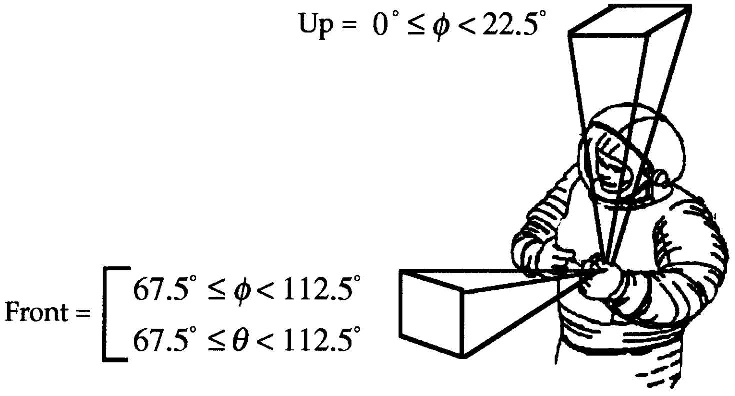


Figure 4.1.7 Example of spherical coordinate projection.

Notice that the activation of the front tactor requires that the target lie within θ= 90 +/- 22.5 degrees, rather than θ= 0 +/- 22.5 degrees. This is a result of Lynx defining the Y_{body} axis out of the chest and the X_{body} axis out the right side so that θ must take on a value of 90 degrees when the subject has zero heading, pitch and roll. Six indicators on the LabView display, one for each tactor, allow the experimenter to view the currently activated tactor pattern.

4.1.4 Experimental Protocol

Six male and six female subjects ranging in age from 21 to 27, participated in the ISS EVA experiments in accordance with the protocol set by the MIT Committee on the Use of Humans as Experimental Subjects (see Appendix C)

Each subject performed the experiment in two two-hour sessions on successive days (referred to as day 1 and day 2, respectively). Each day consisted of one-hour of training and one-hour of experimental trials.

During the training hour of each day, subjects were introduced to the experimental scenario, the input device and the TLS. The subject was first briefed on the dynamics and control of the input device, then shown a sample trial with the ISS model and a target astronaut in view (see Figure 4.1.8). A tour of the ISS included the orientation of the local ISS reference frame, and the names of the modules that the subjects would be asked to maneuver to during the experimental trials. The subject was then given forty-five minutes to practice maneuvering around the ISS and to the target astronaut. Immediately following, the TLS was donned and they were asked to maneuver to a target astronaut in another sample trial, consisting only of an astronaut in close range (see Figure 4.1.9), for an additional fifteen minutes while the vibrotactors were activated. Notice that at the bottom of the screen "distance to target" is printed, with arbitrary units. Subjects were able to gain velocity information by observing the rate at which the distance increased or decreased. The motion was not confined to a particular area around the ISS, therefore it was possible for instances to occur where the ISS and astronaut was out of view, in which case the velocity feedback was crucial.

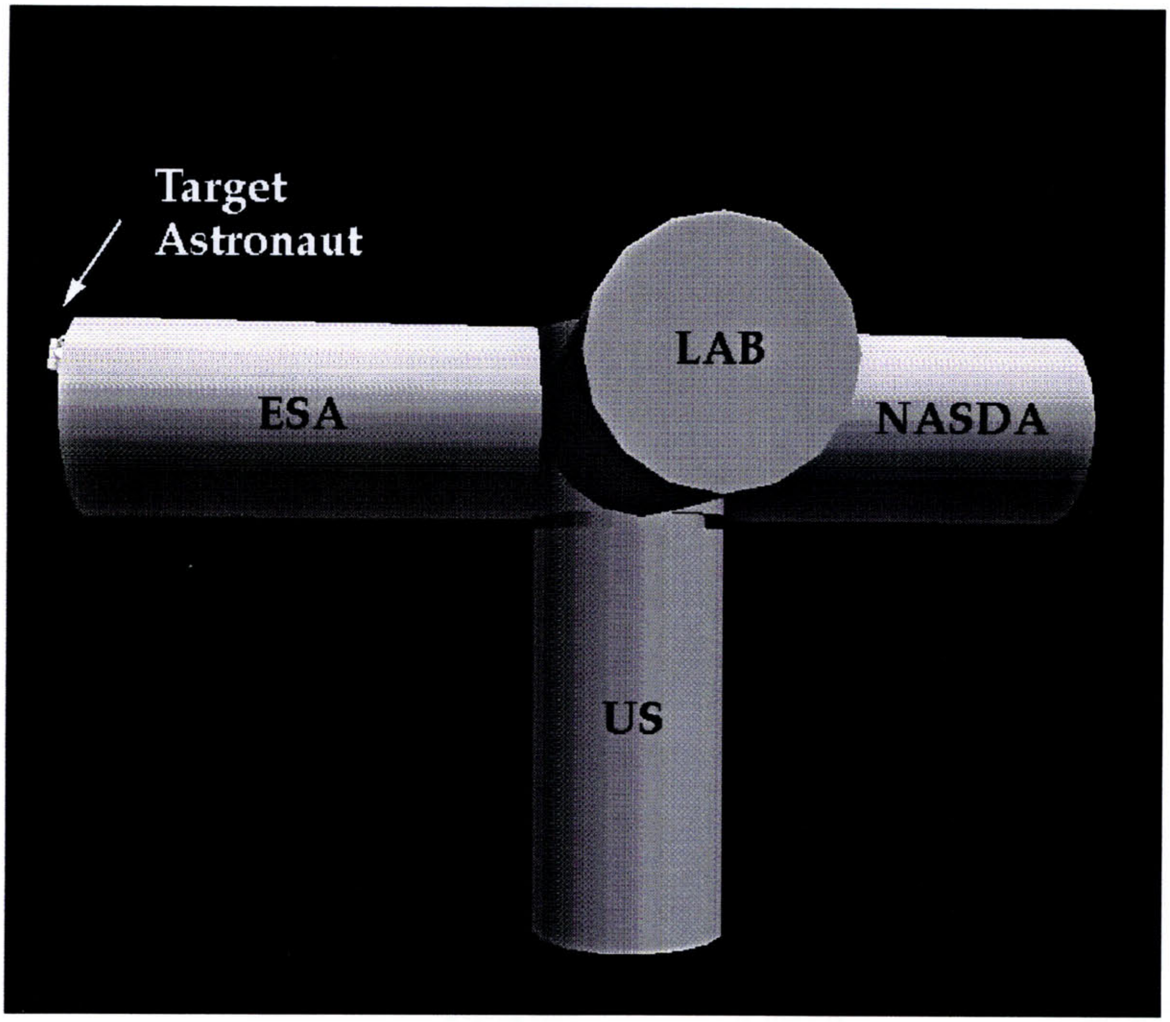


Figure 4.1.8 ISS model and astronaut target training screen.

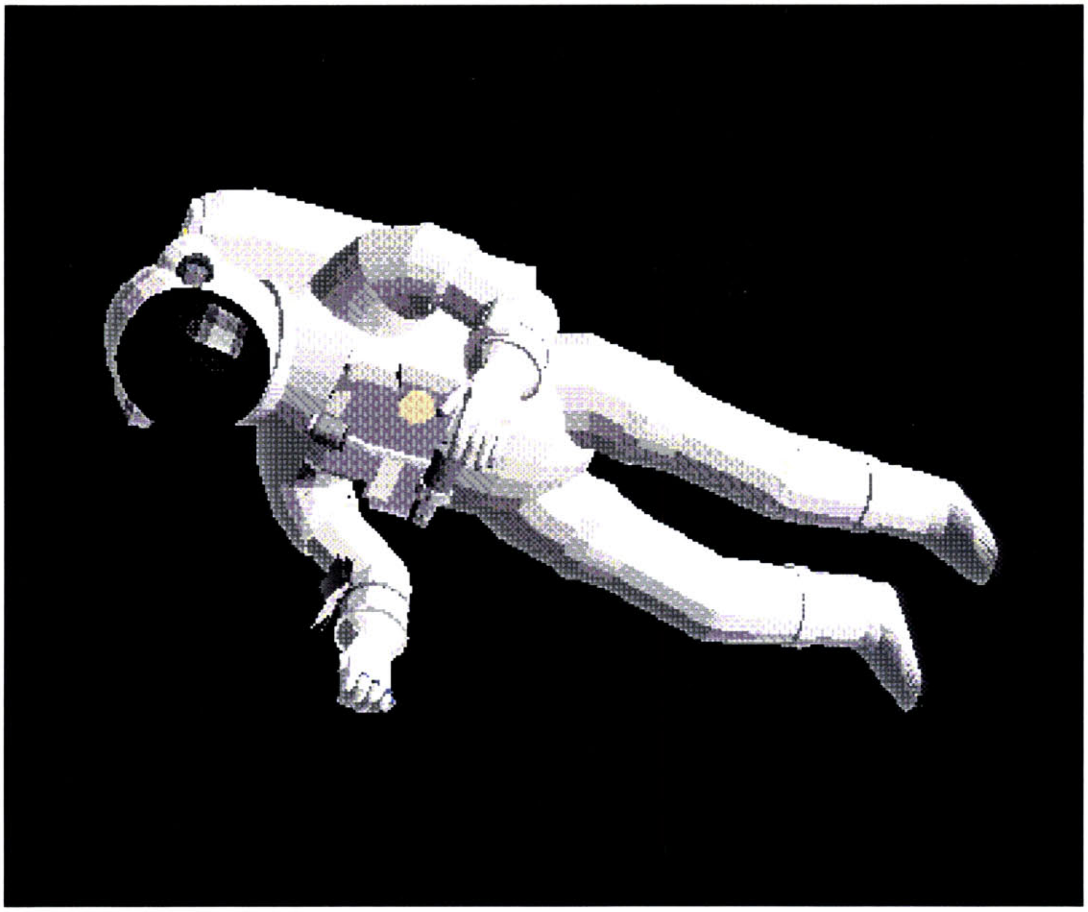


Figure 4.1.9 Close view of target astronaut training screen.

In any given experimental trial, one of four possible scenes was presented to the subject. Each scene differs by path and sense, resulting in four path-sense combinations. There are two general paths, one straight line path and one indirect path. Each path can be traversed in two (opposite) senses, ensuring each scene has its own control being performed throughout the experiment. There were some further distinctions among the four scenes (shown in Figure 4.1.10a-4.1.10d) contributed to their level of difficulty. Scene one (path 0, sense 0) was a straight line path to the target where both the ISS and target were visible at the outset. The subject began at the European Space Agency (ESA) module and ended at the National Space Development Agency of Japan (NASDA) module. Scene two (path 0, sense 1) was the same straight line path traversed in the opposite direction (subjects began at the NASDA module and ended at the ESA module) however, the target was not visible at the outset, nor was the ISS. Before scene two trials, subjects were informed that the station was to their right, regardless of the modality of the trial. Scene three (path 1, sense 0) gave the subjects a view of the ISS from their initial position at the US module, but the target, located at the end of the ESA module, was not in view. Scene four (path 1, sense 0) was approximately the reverse of scene three, however, the subject began the trial on the far side of the ESA module, facing away from the ISS (a corner of which was visible to the subject's far right). In this way, path 1 was designed to be more difficult than path 0, likewise for the senses.

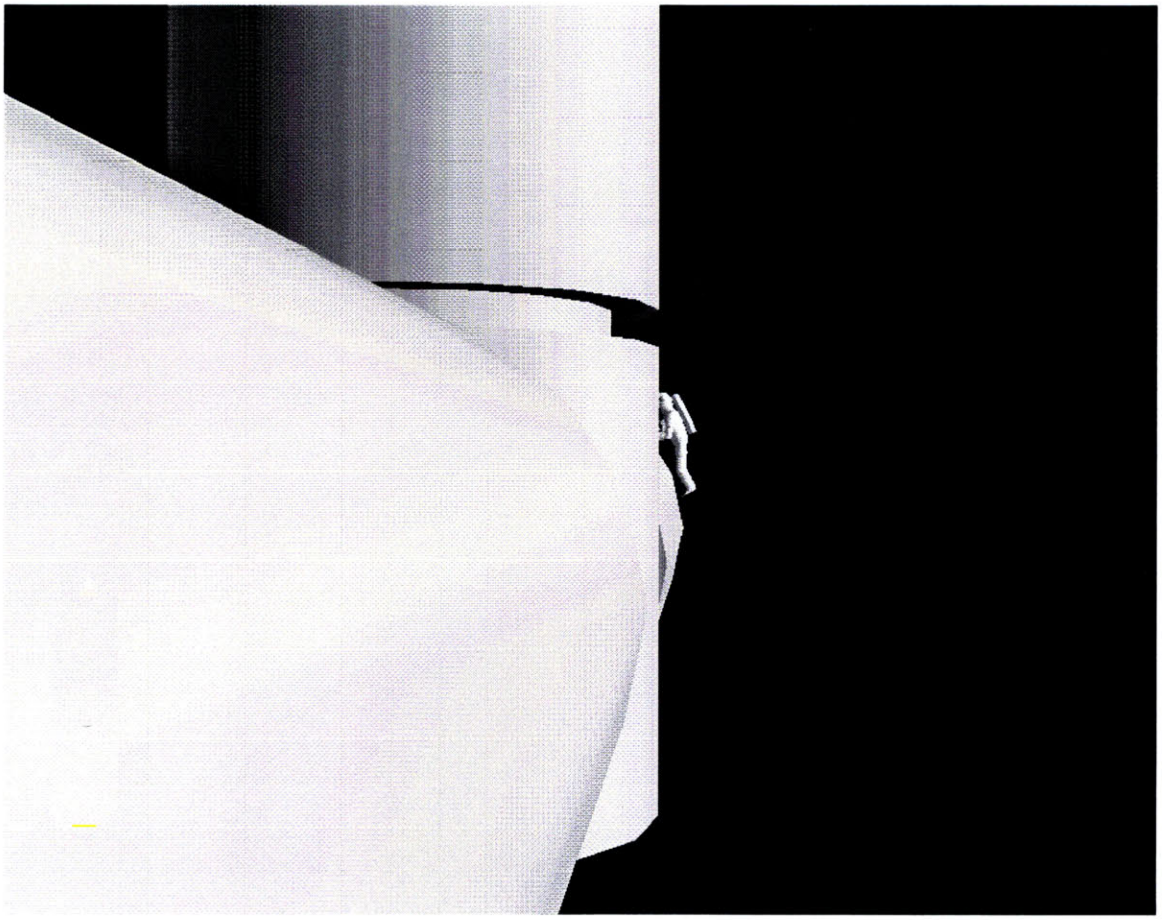


Figure 4.1.10a ISS EVA scene one.

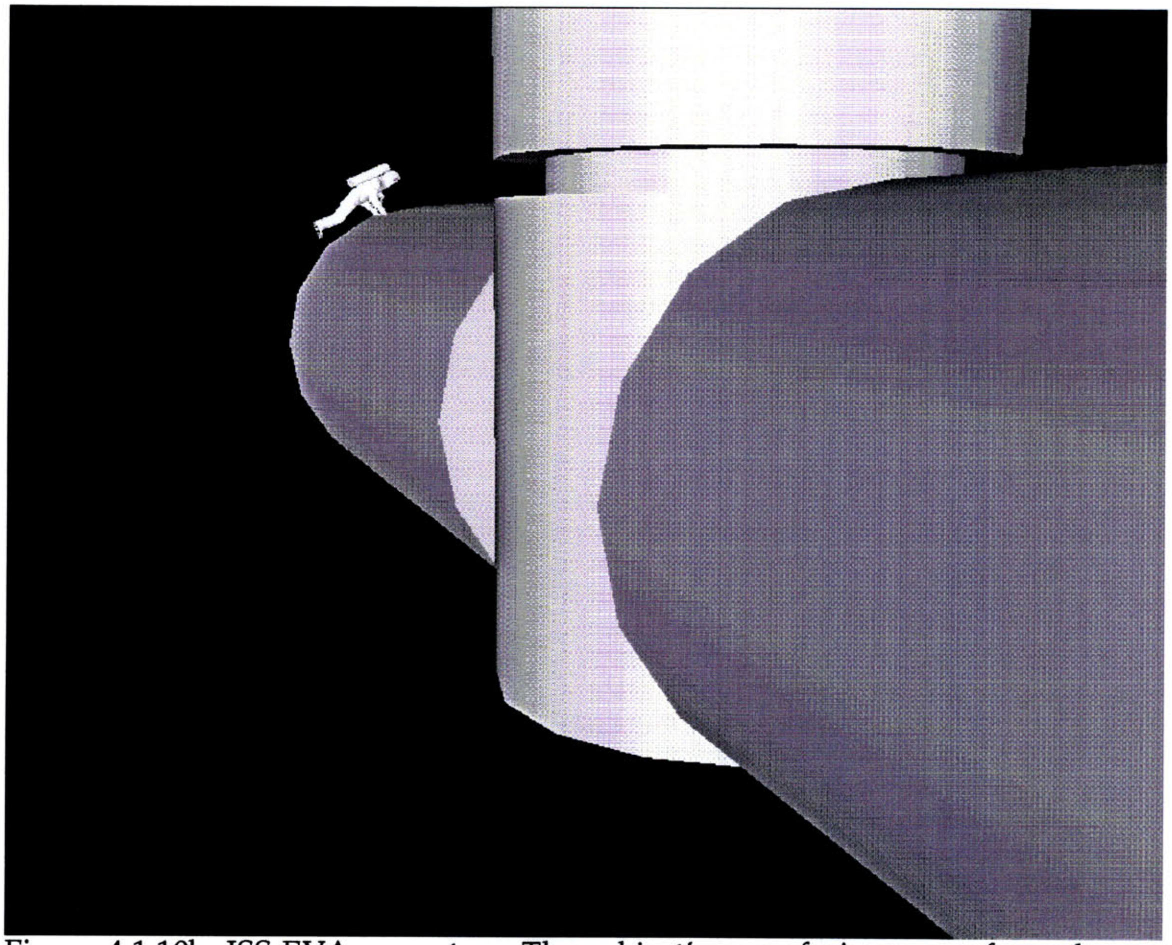


Figure 4.1.10b ISS EVA scene two. The subject's were facing away from the station at the outset, this target could be seen after turning to the right.

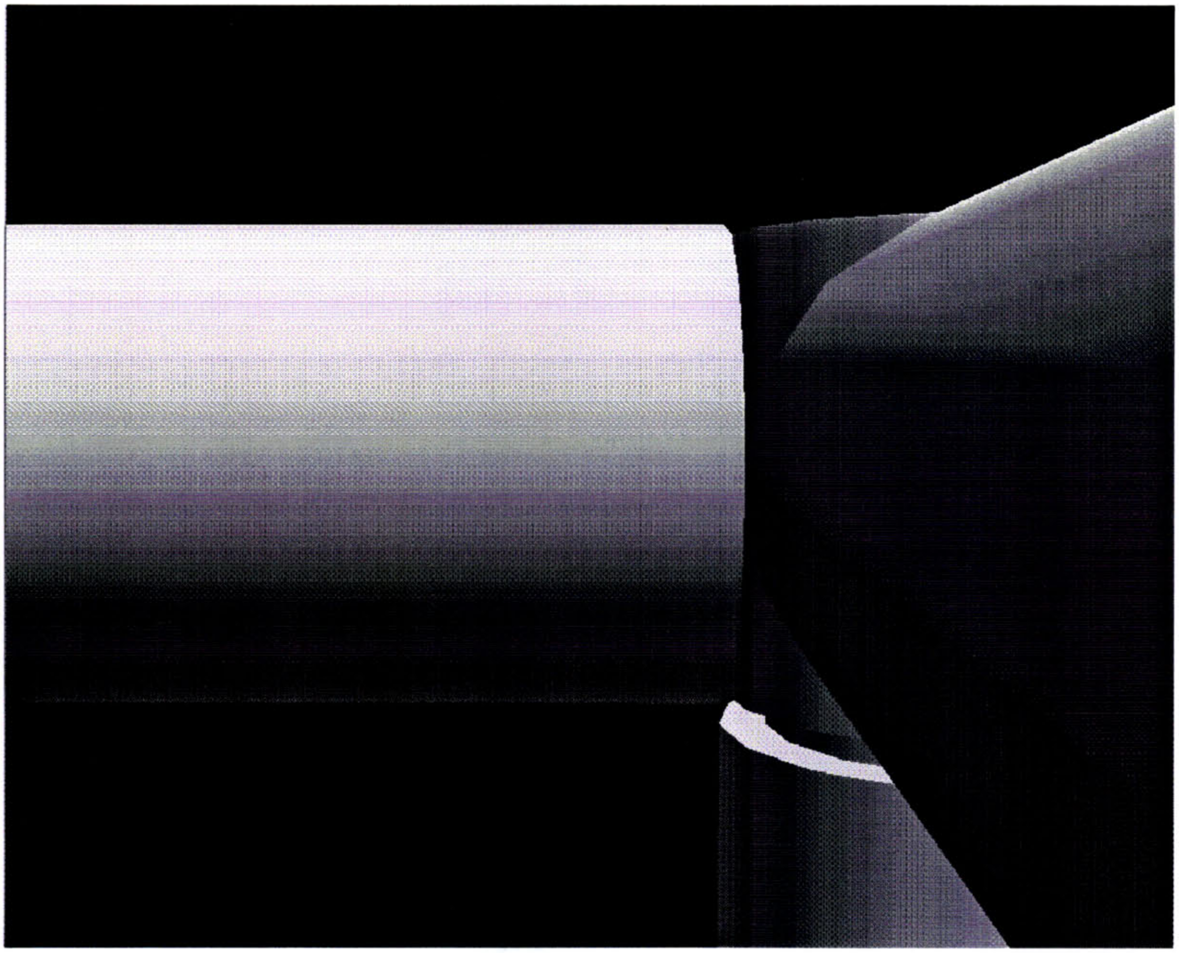


Figure 4.1.10c (1)ISS EVA scene three. The subject view at the beginning of the trial.

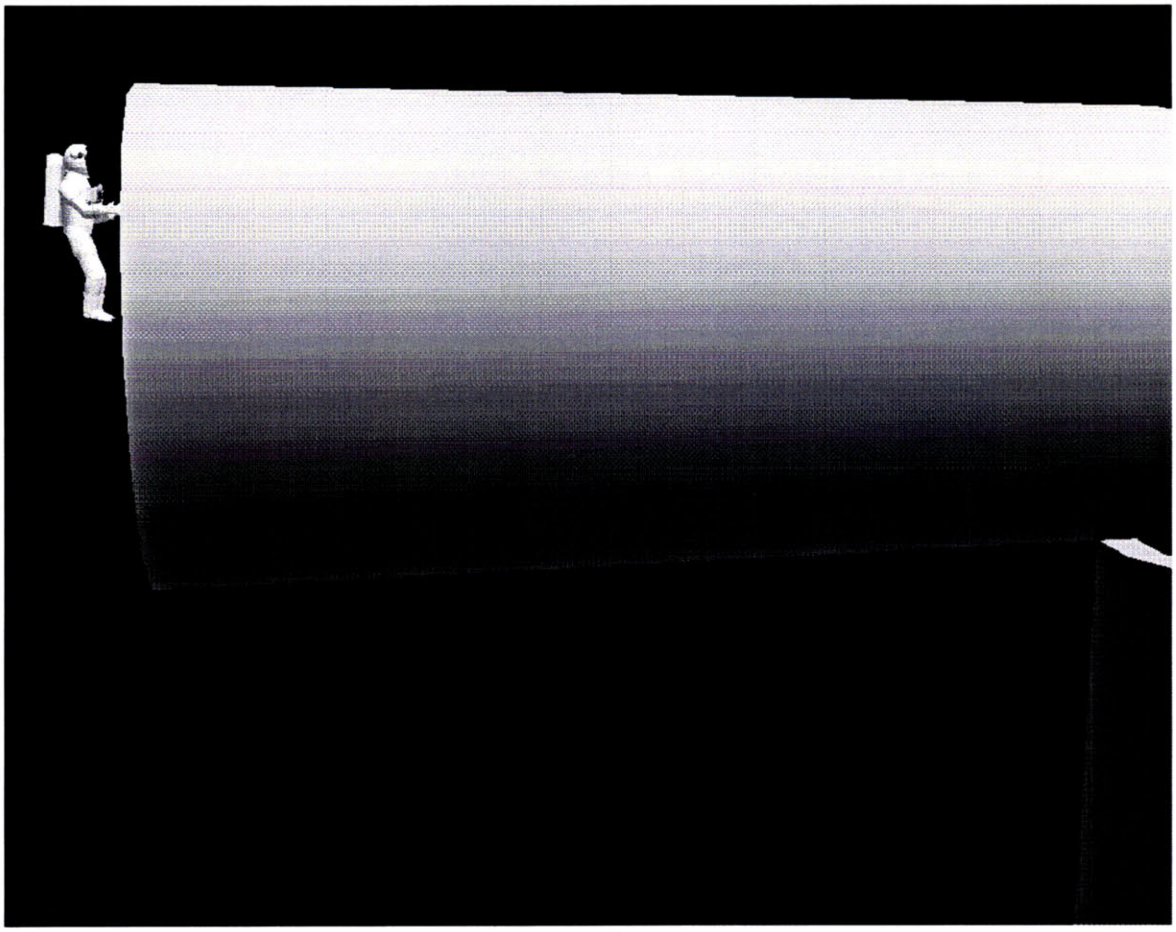


Figure 4.1.10c (2) ISS EVA scene three. The subject view after traveling to the left.

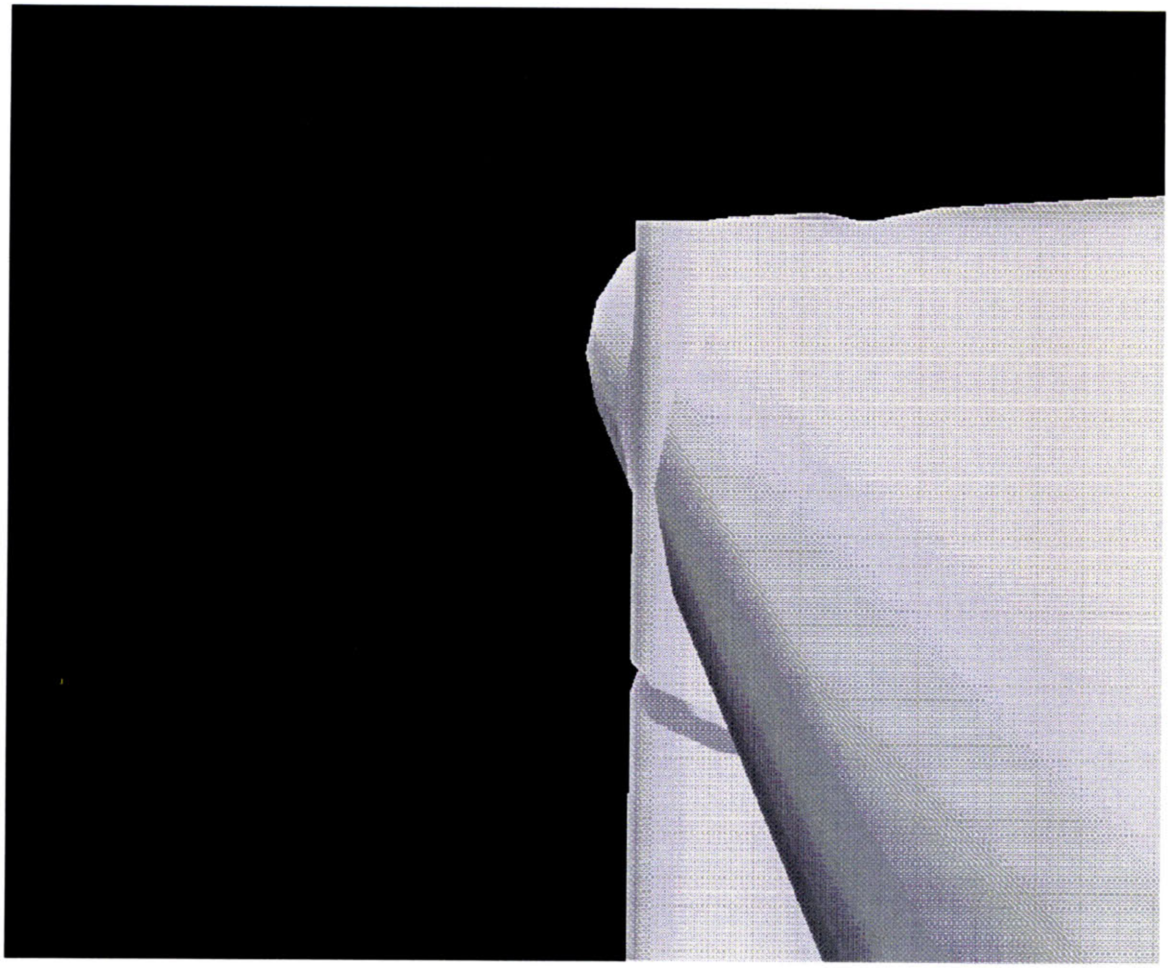


Figure 4.1.10d (1) ISS EVA scene four. The subject view at the beginning of the trial, the target is out of view to the right, opposite the module adjacent to the subject.

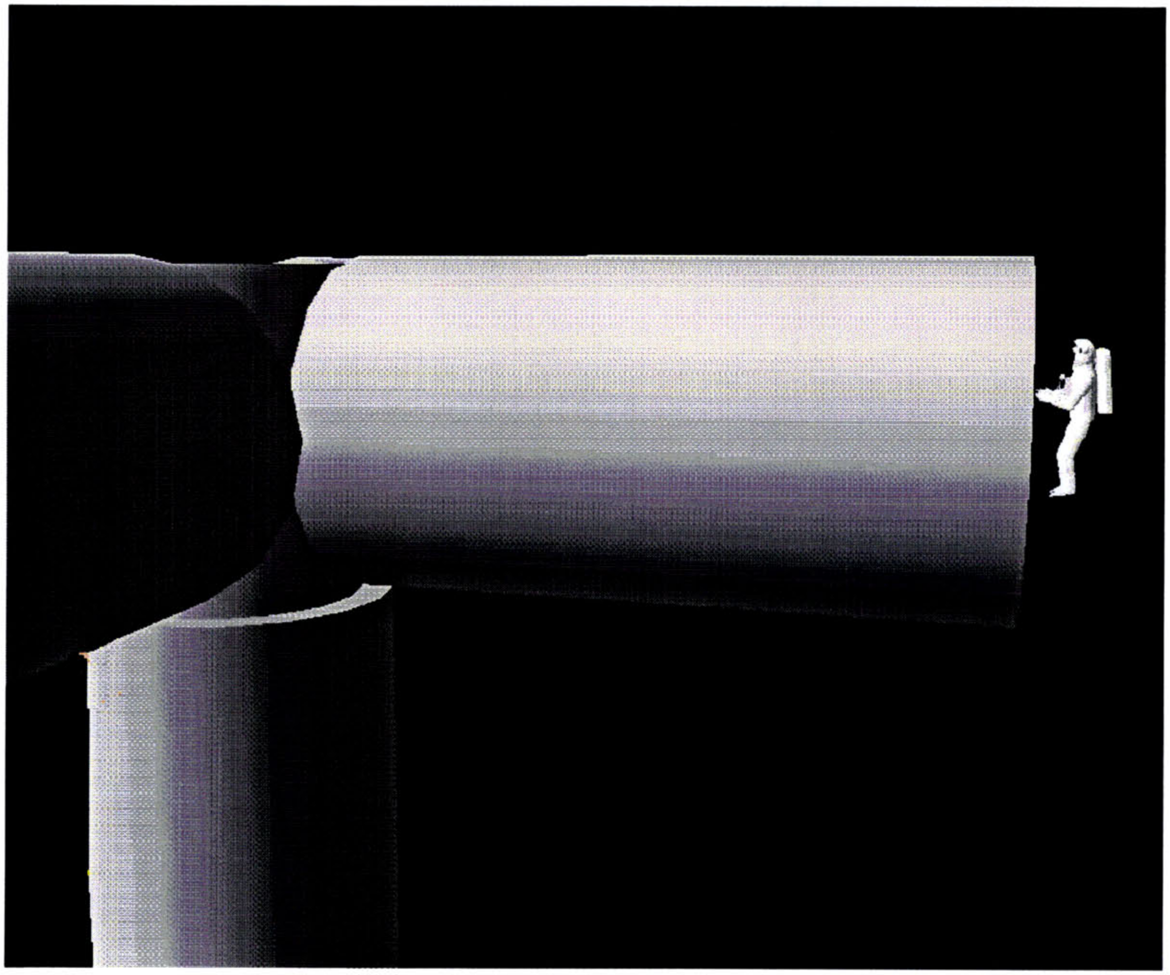


Figure 4.1.10d (2) ISS EVA scene four. The subject view after traveling to the right.

The scenes were presented in a balanced design to insure paired trials. With few numbers of subjects and trials, randomization does not guarantee that all conditions will repeat. Driving the experimental design was the requirement that the modalities alternate with each trial. A given path-sense combination (scene) was repeated twice per day, once with each modality (0 and 1, without and with tactors, respectively), for a total of eight trials per day. Table 4.1.1a gives the design elements while Table 4.1.1b shows all possible design configurations.

Table 4.1.1 ISS EVA protocol design elements.

(a)

Element	Path Sense Pairs
a	00 10
a′	10 00
a*	11 01
a′*	01 11

(b)

	Configuration	Elements	P-S			
Modality			0 1	0 1	0 1	0 1
	A	a a* a′ a*	00 01	11 01	10 00	01 11
	A′	a′ a′* a a*	10 00	01 11	00 10	11 01
	A*	a* a a′* a′	11 01	00 10	01 11	10 00
	A′*	a′* a′ a* a	01 11	10 00	01 11	00 10

Each configuration delivers each path and sense with equal frequency, and each path-sense pair as frequently with each modality (note that only one configuration is performed per day). The final design (shown in Table 4.1.2) incorporates only configurations A and A* to generate the greatest difference across trial days, note that the design is fully replicated across gender.

Table 4.1.2 Final ISS EVA protocol design.

Subject # Gender = M/F	Day 1	Day 2
1/7	A	A*
2/8	A*	A
3/9	A	A*
4/10	A*	A
5/11	A	A*
6/12	A*	A

At the onset of trials conducted without tactors, subjects were told which module of the ISS the target was located. At the onset of tactor trials, the vibrotactile stimulus relayed the position vector to the target. Reaction time (RT) and movement time (MT) were recorded for each trial. Reaction time was measured as the time between the onset of the tactile of auditory stimulus, and the first movement of the spaceball. Movement time was recorded as the time from the tactile or auditory stimulus onset, to target acquisition. Target acquisition was complete when the subject reached within one hundred units of the target astronaut. Due to the difficulty associated with controlling the six dof (degree of freedom) spaceball, it was not uncommon for subjects to lose control of their motion during the trials. In the event that the subject could no longer control the spaceball, the trial was stopped. The subject could re-attempt the trial once, immediately following the failure. If the second attempt was successful, that movement time was recorded, however the reaction time from the first (failed) trial was recorded for data analysis. With prior knowledge of the scene at the onset of the second attempt, only the subject's reaction to the scene the first time it is viewed is a valid measure of reaction time.

4.1.5 Data Analysis

An individual trial was labeled with the following variables: subject, gender, day, path, sense, modality, failure, repetition and trial number. Data were organized into sixteen different trial conditions, shown in Table 4.1.3, that varied by modality, path, sense and day.

Table 4.1.3 Trial conditions as a function of modality, path, sense and day.

Condition	Modality - Path - Sense - Day	Condition	Modality - Path - Sense - Session
1	0000	9	1000
2	0001	10	1001
3	0010	11	1010
4	0011	12	1011
5	0100	13	1100
6	0101	14	1101
7	0110	15	1110
8	0111	16	1111

Repeated measures analysis determined the statistical significance of the main and cross effects of tactors, path, sense and session on subject performance. The effect of tactors (measured in seconds), for example, can be described by Equations 1 and 2

$$RT_{nt} - RT_t = \text{effect} \qquad (1)$$

$$MT_{nt} - M_t = \text{effect} \qquad (2)$$

where t refers to a tactor trial and nt refers to a non-tactor trial. A positive effect for a given condition indicates that the tactile stimulus decreased the time required to either initially react, or maneuver to the target, respectively. Once the times have been subtracted across conditions to determine the tactor effect, only eight path-sense-day conditions (P-S-D code) remain, and are shown in Table 4.1.4.

Table 4.1.4 Path-Sense-Day code.

Conditions Subtracted	P-S-D code
1 - 9	x000
2 - 10	x001
3 - 11	x010
4 - 12	x011
5 - 13	x100
6 - 14	x101
7 - 15	x110
8 - 16	x111

The model for RT and MT for the ith subject and jth trial is as follows

$$RT_{ij} = \mu + \alpha + \beta + \gamma + \delta + \eta + \alpha\,\beta + \alpha\,\gamma + \alpha\,\delta + \alpha\,\eta + \varepsilon_{\alpha\beta\gamma\delta\eta} \quad (3)$$

$$MT_{ij} = \mu + \alpha + \beta + \gamma + \delta + \eta + \alpha\,\beta + \alpha\,\gamma + \alpha\,\delta + \alpha\,\eta + \varepsilon_{\alpha\beta\gamma\delta\eta} \quad (4)$$

where μ is the mean, ε is the normally distributed error estimate and α, β, γ, δ, η are theoretical main effects of tactors, path, sense, day and subject, respectively, and their products, the cross effects. This process assumes that differences taken between modalities within a subject eliminates the subject effect. This is valid if the differences for a given subject across all conditions are normally distributed, as was found to be the case (discussed in Chapter 5, Results).

5. RESULTS

This chapter presents the results of the experimental study outlined in Chapter 4, Methods. Main effects, are presented first for reaction time and then movement time, followed by cross effects, individual subject effects and analysis of failed trials.

5.1 Effect of Tactors

Table 5.1.1 summarizes the repeated measures analysis main effects and cross effects of tactors on both RT and MT. Table 5.1.1 reveals that tactile cueing results in a significant decrease in the time required to initially react to the scene, saving the subject approximately 4.5 s at the outset (mean effect of tactors for RT). Notice that the number of cases (n) varies depending on the number of trials with missing data points (as a result of failed attempts) for a given condition and subject. RT was also shown to decrease significantly from day one to day two. Both the main and cross effect of sense on RT was significant, with sense 0 requiring more time to react than sense 1, and tactile cues offering more assistance for sense 0 than sense 1. Notice that the only significant effect for movement time is the main effect of tactors, therefore the approximately 92 time savings to acquire the target, is provided by tactile cues alone, without other significantly influencing factors (Figure 5.1.1 shows the main effect of tactors versus the path-sense-day code). Although the effect of day on MT is not statistically significant, it suggests a trend that subjects maneuvered to the target on average 40 s faster on day 2 than on the first day, indicative of a training effect.

5.2 Subject Effects

Figures 5.2.1a and 5.2.1b shows the Subject variances for RT and MT. Individual subject variances are consistent with the exception of Subjects 1 and 3 for RT, and 6, 8 and 11 for MT.

Table 5.1.1 Main and Cross effect statistics for RT and MT

	Effects	n[3]	t[4]	p[5]	Mean Effect[6] (s)
Reaction Time (RT)					
Main Effects	Tactors (T)	92	3.381	**0.001**	**4.55**
	Path (P)	92	-1.924	0.058	-2.816
	Sense (S)	92	2.363	**0.02**	**3.285**
	Day (D)	92	5.285	**0.001**	**7.091**
Cross Effects	TXP	44	0.472	0.639	1.465
	TXS	45	4.288	**0.001**	**10.31**
	TXD	44	1.672	0.102	3.884
Movement Time (MT)					
Main Effects	Tactors (T)	55	3.936	**0.001**	**91.769**
	Path (P)	61	1.947	0.056	35.203
	Sense (S)	58	0.314	0.755	6.987
	Day (D)	56	1.993	0.051	39.245
Cross Effects	TXP	24	-0.412	0.684	-17.13
	TXS	21	1.155	0.262	64.356
	TXD	19	1.903	0.073	77.944

---

[3] n is the number of completed trial differences used to compute the various statistics for a given effect. If all subjects had sucessfully completed every trial, there would be (for Main effects) a maximum of 96 differences. For cross effects, there are at most 8 differences per subject and therefore a maximum of 48 cases. This number (n) varies because it depends on the number of failures (and on the path, sense and day code of that failure).

[4] The value of t is a measure of the significance of the correlation between either RT or MT, and a particular variable (path, sense, day). It tests the significance of a given coefficient in equations 3 and 4.

[5] The p value, or probability value, is a quantification of the statistical significance of a given effect (or the confidence of a statistical measure). For this research, an effect is statistically significant if the symmetric confidence interval is greater thant the 95th percentile (or $p<0.05$).

[6] Note that the mean effect is not the mean value of RT of MT, it is the mean value of the effect (which is a diffrence), as described in Chapter 4, Methods.

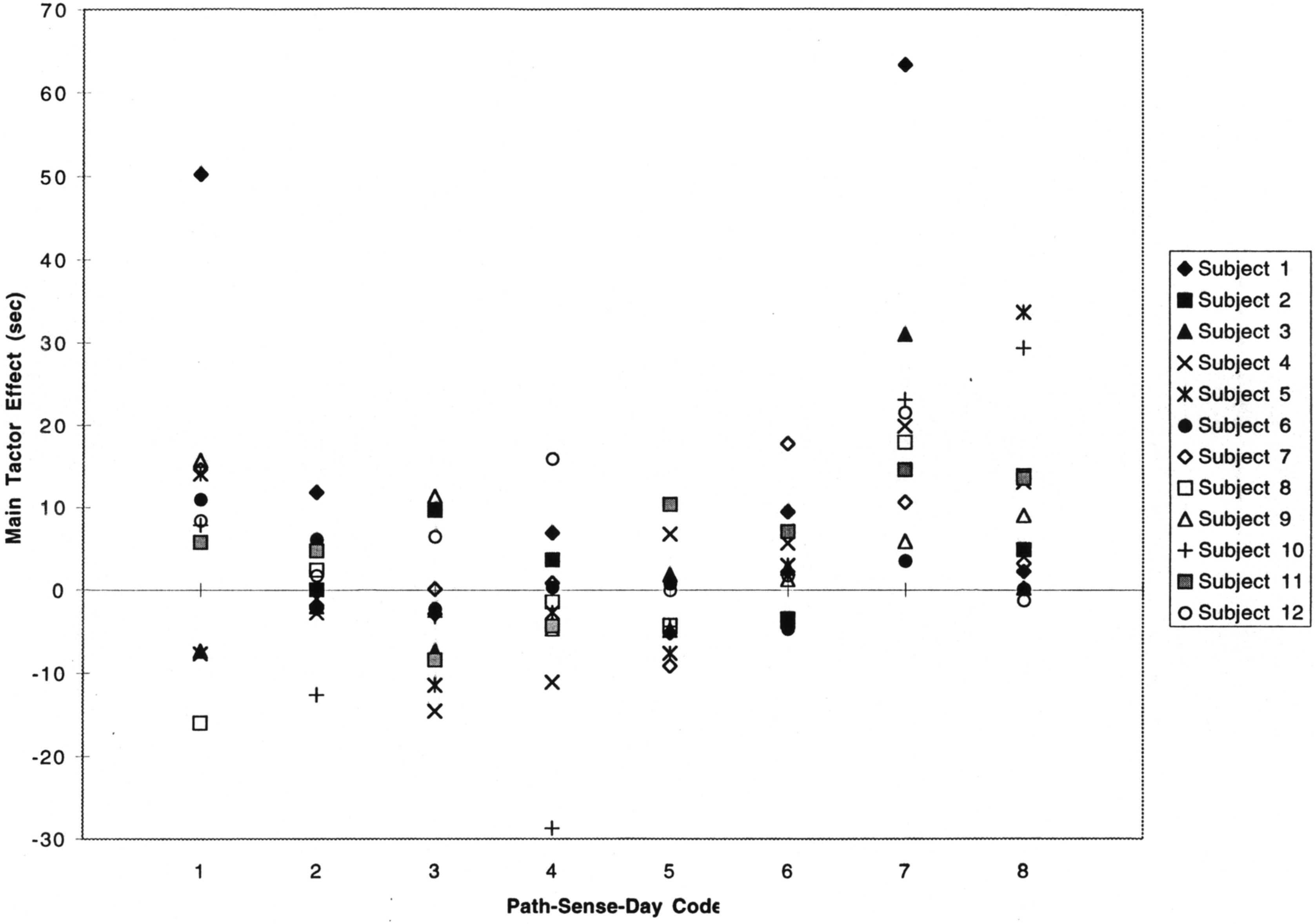


Figure 5.1.1 Main effect of tactors versus path-sense-day code for all subjects.

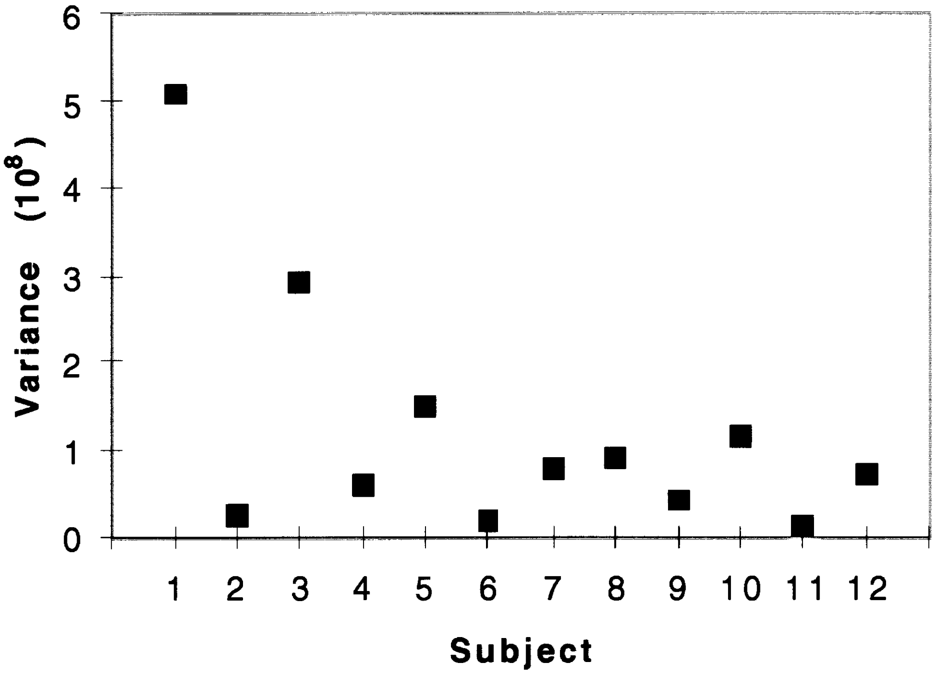


Figure 5.2.1a Subject variances for reaction time.

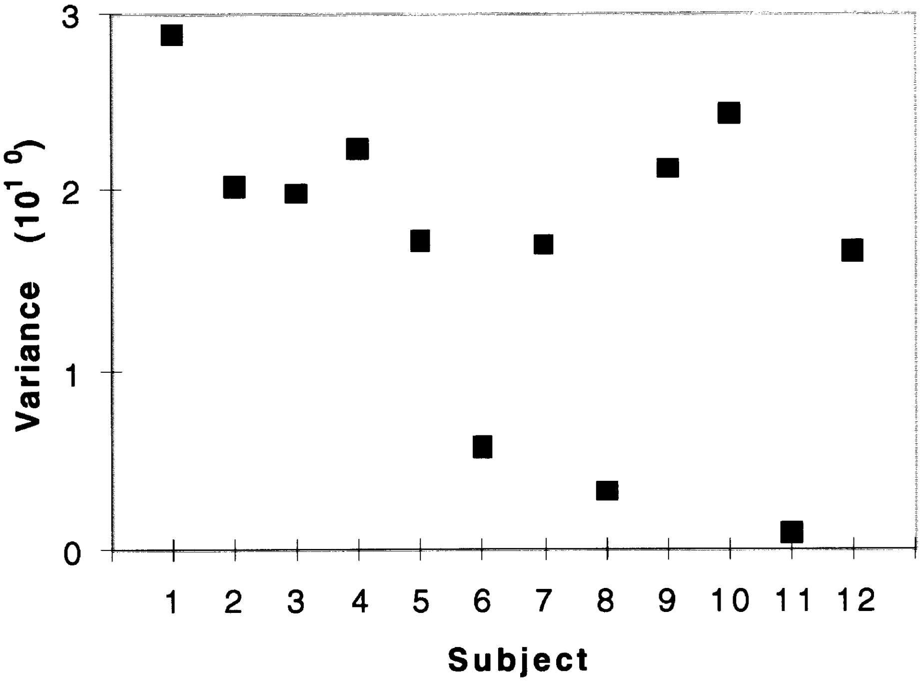


Figure 5.2.1b Subject variances for movement time.

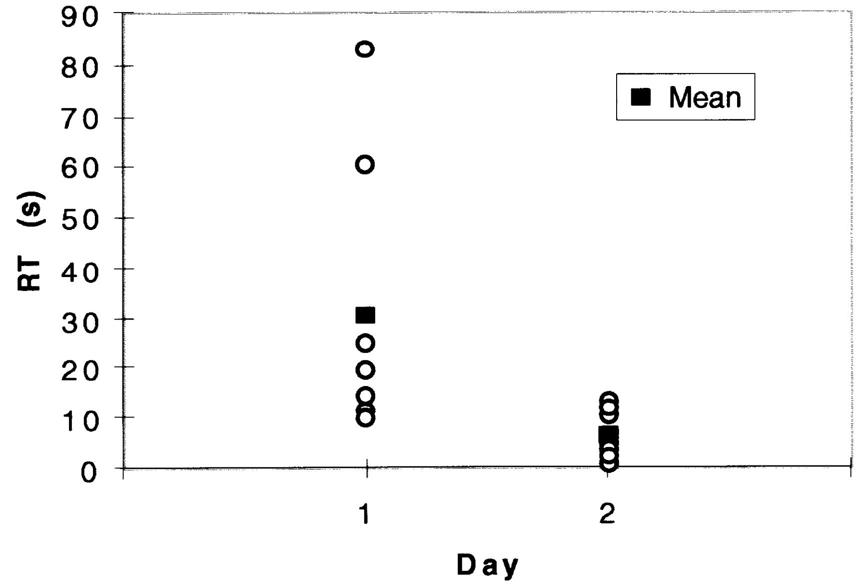


Figure 5.2.2 Reaction time versus day for subject 1.

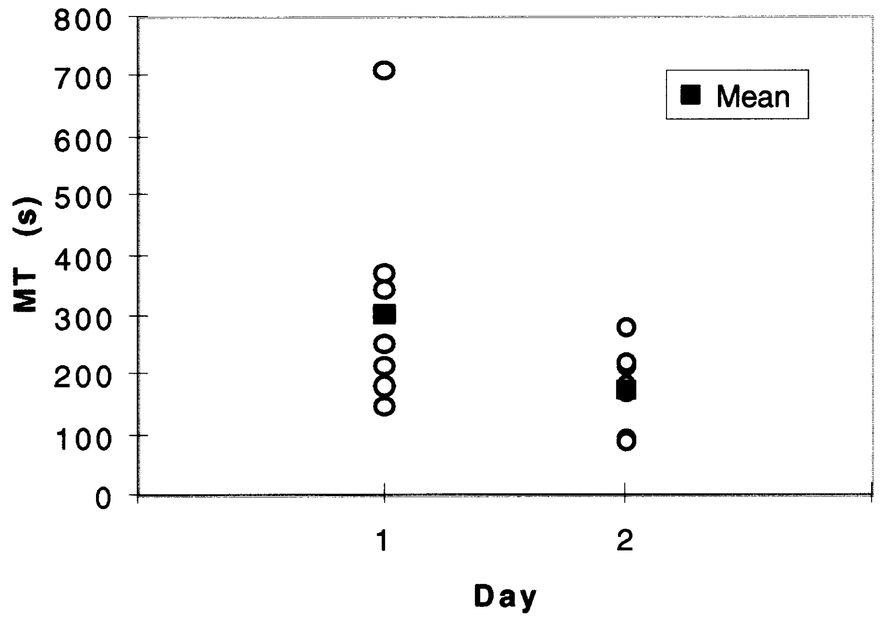


Figure 5.2.2 Movement time versus day for subject 1.

5.2.2a,b shows RT and MT as a function of day for subject 1. The mean RTs are significantly different (n=16, F=6.304, p=0.025), with the subjects reacting approximately 25 s faster on day two than on day one. Although the MT means across all subjects do not differ significantly (N=15, F=2.729, p=0.122), Subject 1 in particular, acquired the target an average of 2 minutes faster on day 2 than day 1, consistent with a change in control strategy as will be discussed in section 5.4, Discussion. Figure 5.2.3a shows RT versus Day for subject 3. Again the mean is significantly smaller (n=16, F=5.013, p=0.042) on day 2, with a decrease in RT of approximately ten s from day 1 to day 2. Figure 5.2.3b-5.2.3d plots MT versus Day for subjects 6, 8 and 11, respectively.

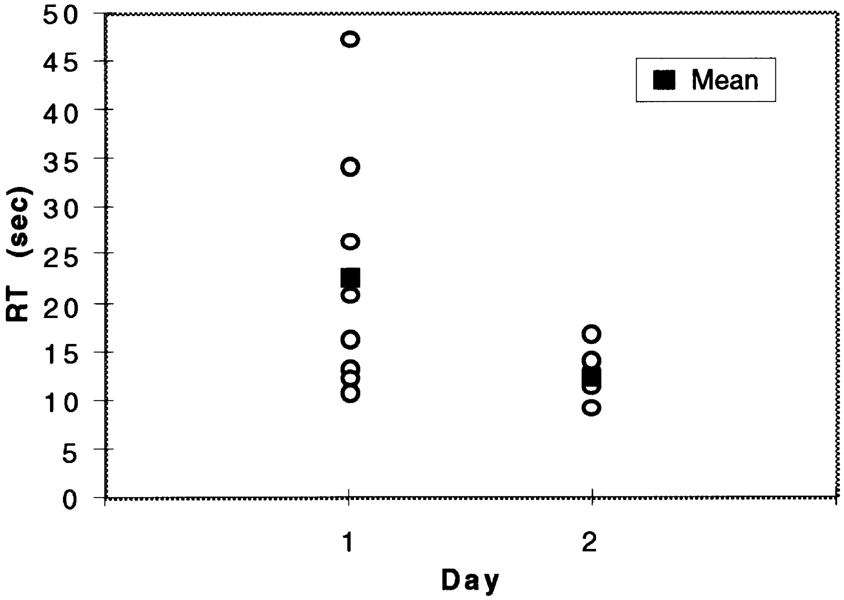


Figure 5.2.3a Reaction time versus day for subject 3

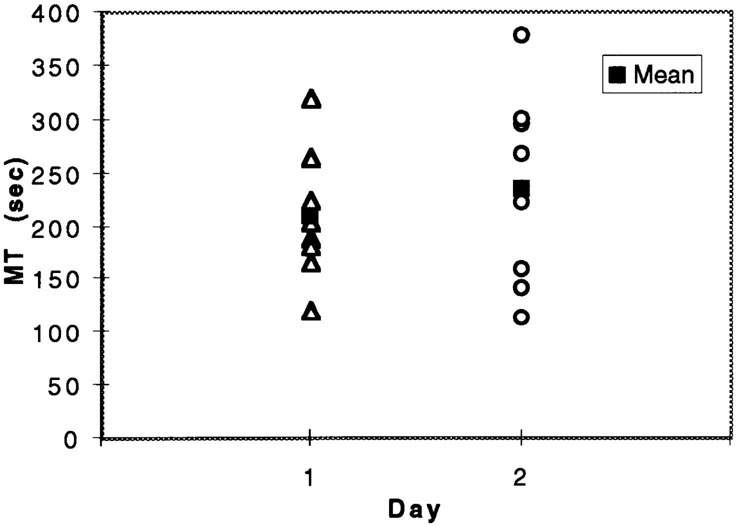


Figure 5.2.3b Movement time versus day for subject 6.

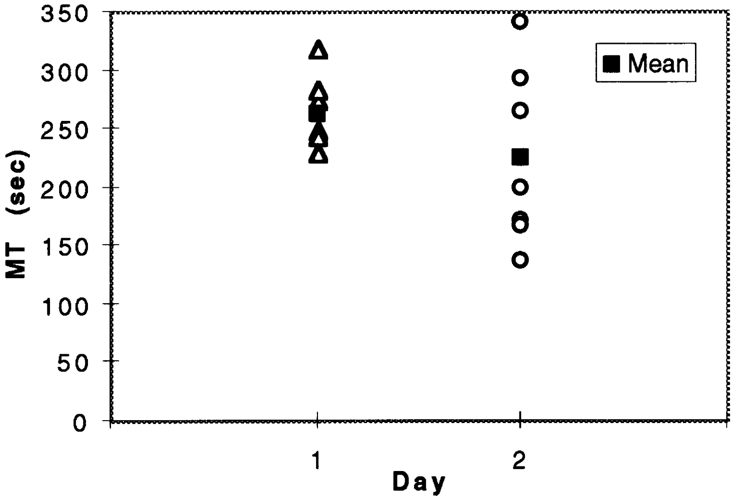


Figure 5.2.3c Movement time versus day for subject 8.

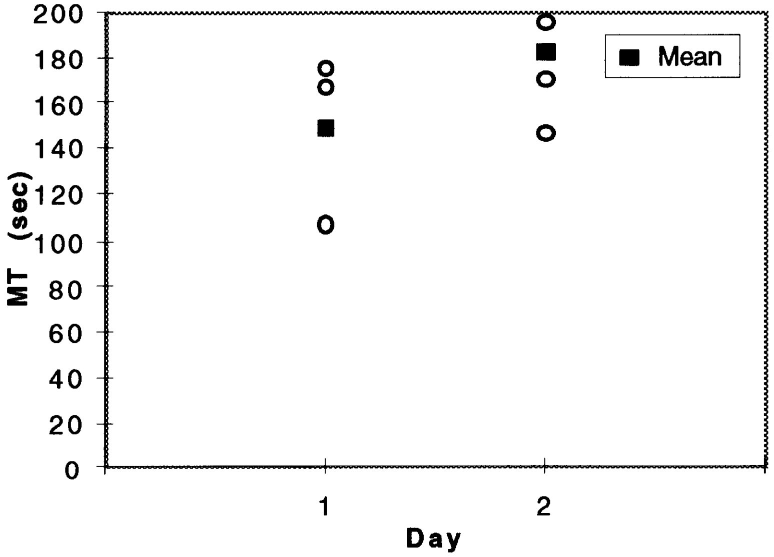


Figure 5.2.3d Movement time versus day for subject 11.

Indicative of the low variances for these subjects, their means do not differ significantly across days, suggesting a consistent control strategy from session to session.

The effect of trial order (for a given day) on RT and MT was calculated for the five subjects mentioned above. Reaction time is illustrated in Figure 5.2.4a-5.2.4e, and movement time is illustrated in Figure 5.2.5a-5.2.5e.

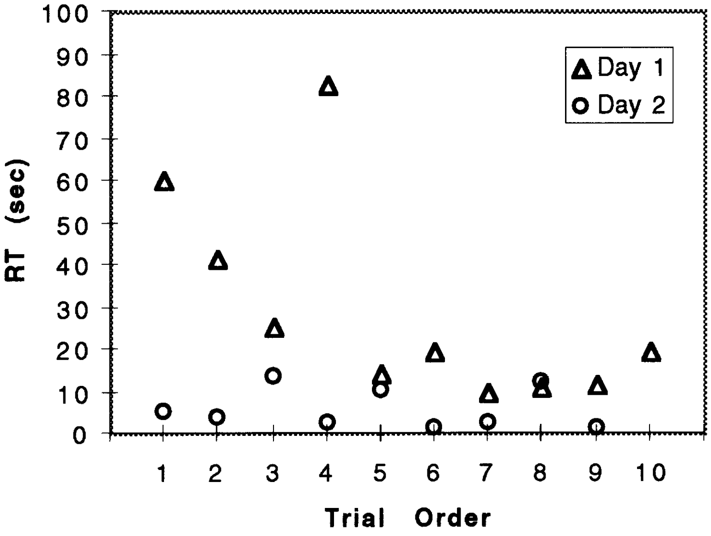


Figure 5.2.4a Reaction time versus trial order for subject 1.

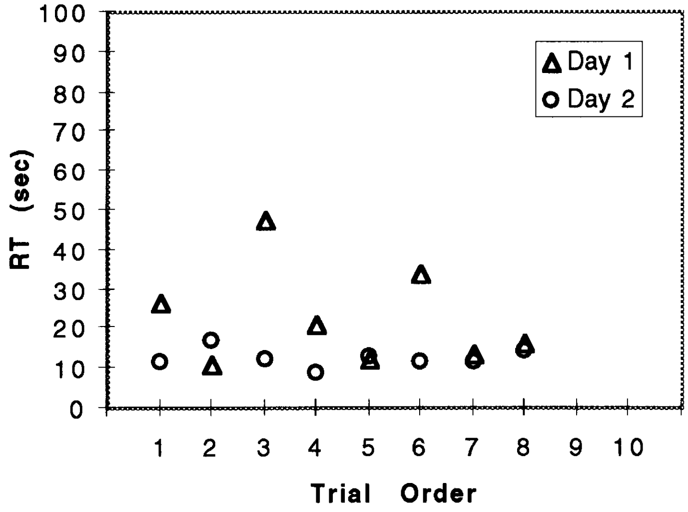


Figure 5.2.4b Reaction time versus trial order for subject 3.

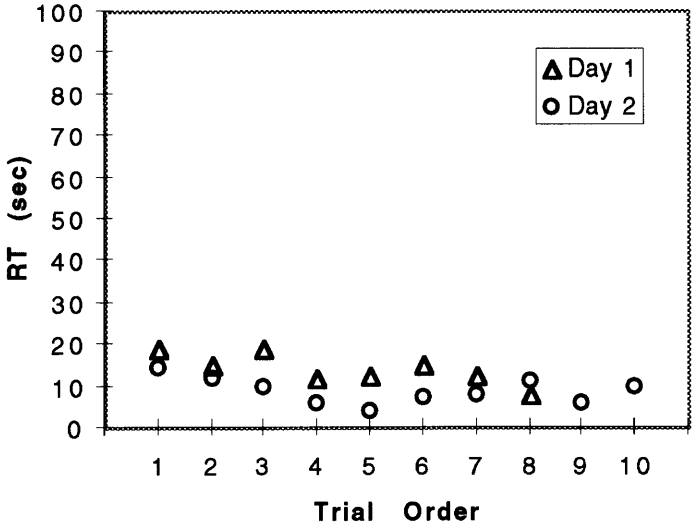


Figure 5.2.4c Reaction time versus trial order for subject 6.

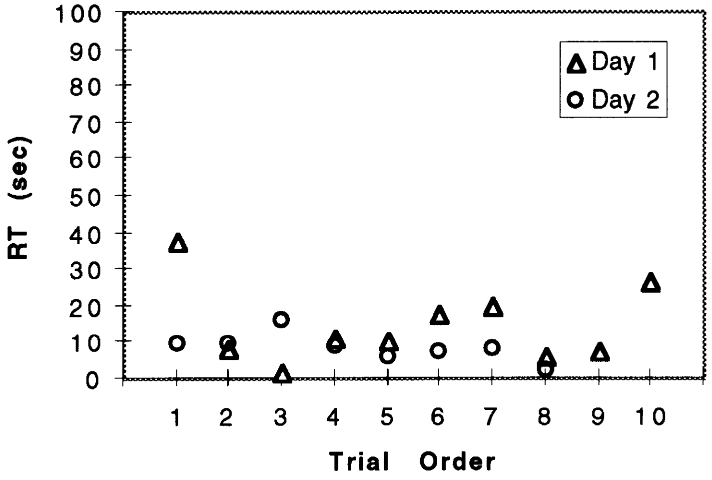


Figure 5.2.4d Reaction time versus trial order for subject 8.

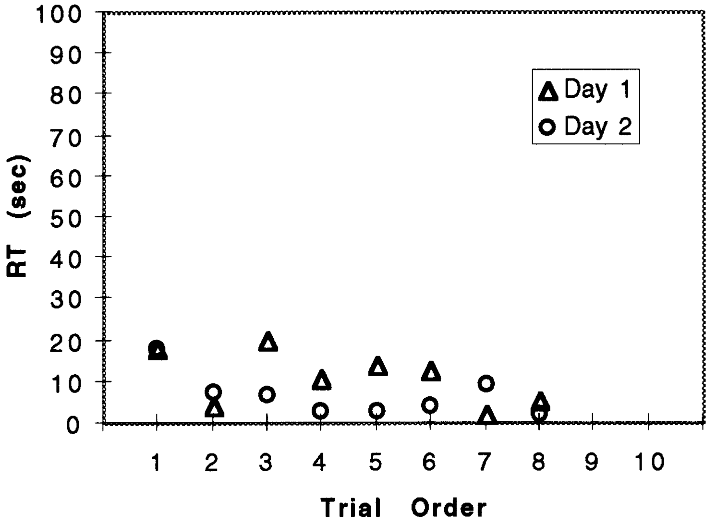


Figure 5.2.4e Reaction time versus trial order for subject 11.

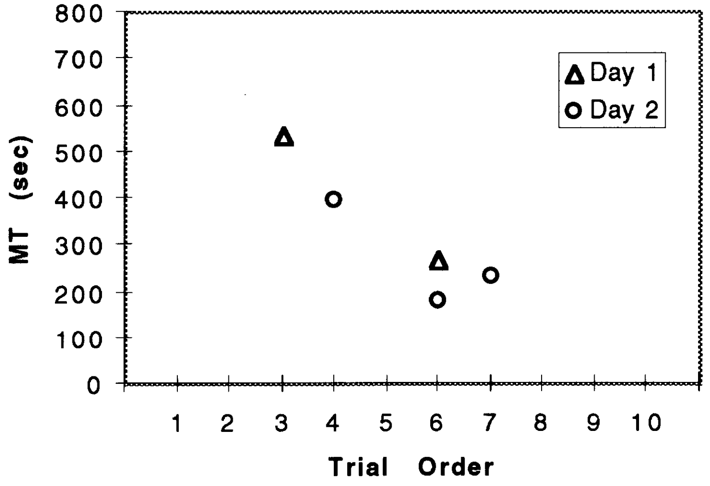


Figure 5.2.5a Movement time versus trial order for subject 3.

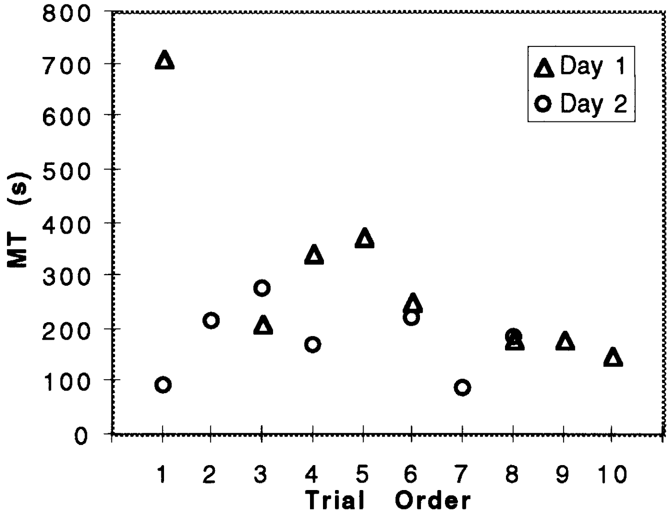


Figure 5.2.5b Movement time versus trial order for subject 1.

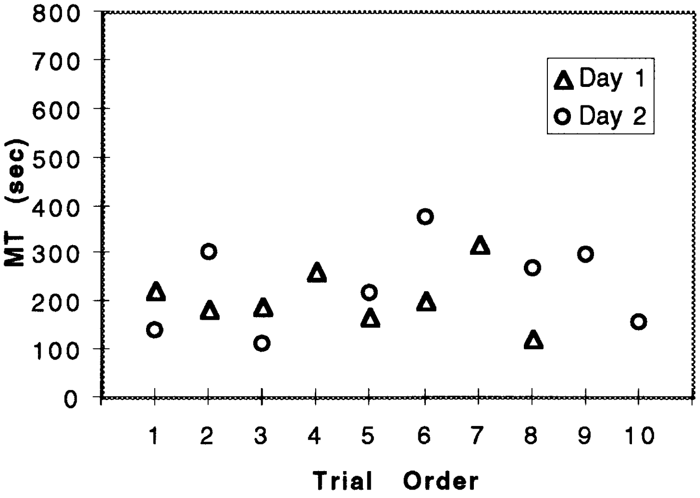


Figure 5.2.5c Movement time versus trial order for subject 6.

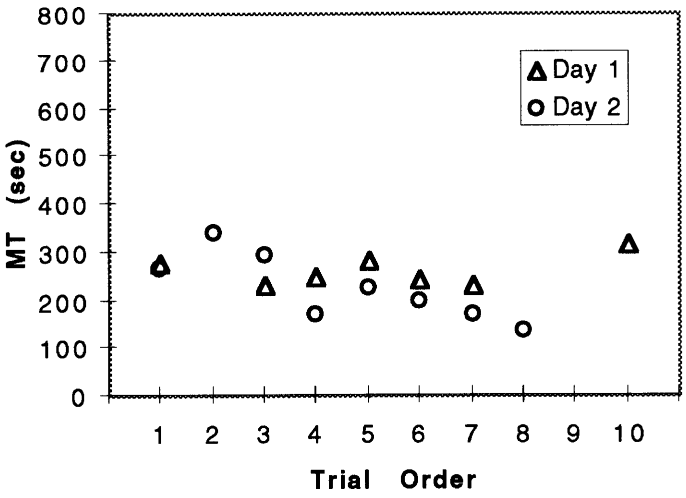


Figure 5.2.5d Movement time versus trial order for subject 8.

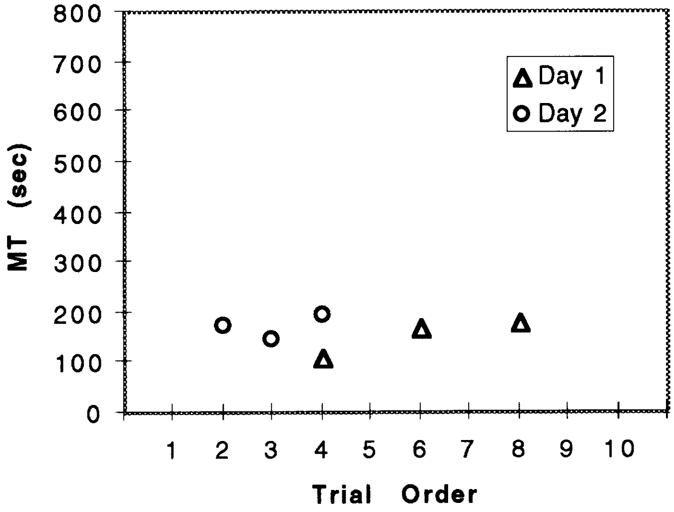


Figure 5.2.5e Movement time versus trial order for subject 11.

For subject 1, the first three RT's show a steady decrease, however trial number four shows a dramatic rise. This was the first non-tactor trial for scene 3 (path 1, sense 0) where the subject had to discern their location on the space station so that the verbal cue could be interpreted, and hence chose an initial direction of motion. Subject 3 showed a similar result for the same scene in trial 3 of the first day. Subject 6 displays no obvious trend, however, trial 6 on day 2 had a high MT as a result of a near miss at the target from which he recovered. Figure 5.sub8MT reveals an almost steady decline in MT on day 2 (with the exception of trial 4) suggesting that learning was still occurring on day 2. While subject 11 experienced many failures, those trials that were successful have consistent MT's that differ by a maximum of approximately 80 s, hence the low variance exhibited in Figure 5.2.5e.

5.2.1 Gender Effects

A fully factorial analysis of variance (ANOVA) revealed the effect of gender on RT, MT, variances and failures. Table 5.2.1 summarizes the gender effects and reveals a significant difference only in RT with women reacting an average of 3 s faster than men.

Table 5.2.1 Gender effects; n is the number of cases, F denotes the F-ratio statistic and p denotes the statistical significance.

	n	F	p	Mean (s)
RT	209	6.67	0.01	male=15.78 female=12.05
MT	141	1.74	0.19	male=297.57 female=334.16
Variance of RT	12	1.77	0.21	male=6.73x10^{7} female=1.73x10^{8}
Variance of MT	12	1.06	0.33	male=1.38x10^{11} female=1.90x10^{11}
Number of Failures	24	0.25	0.62	male=3.17 female=2.75

5.3 Analysis of Failed Trials

The Figures in section 5.1 display times for only the successful trials, therefore it is necessary to look at the combined effect of day on the number of failures. Figure 5.3.1 shows the percentage of failures (normalized to 8 trials) in a given day for each subject.

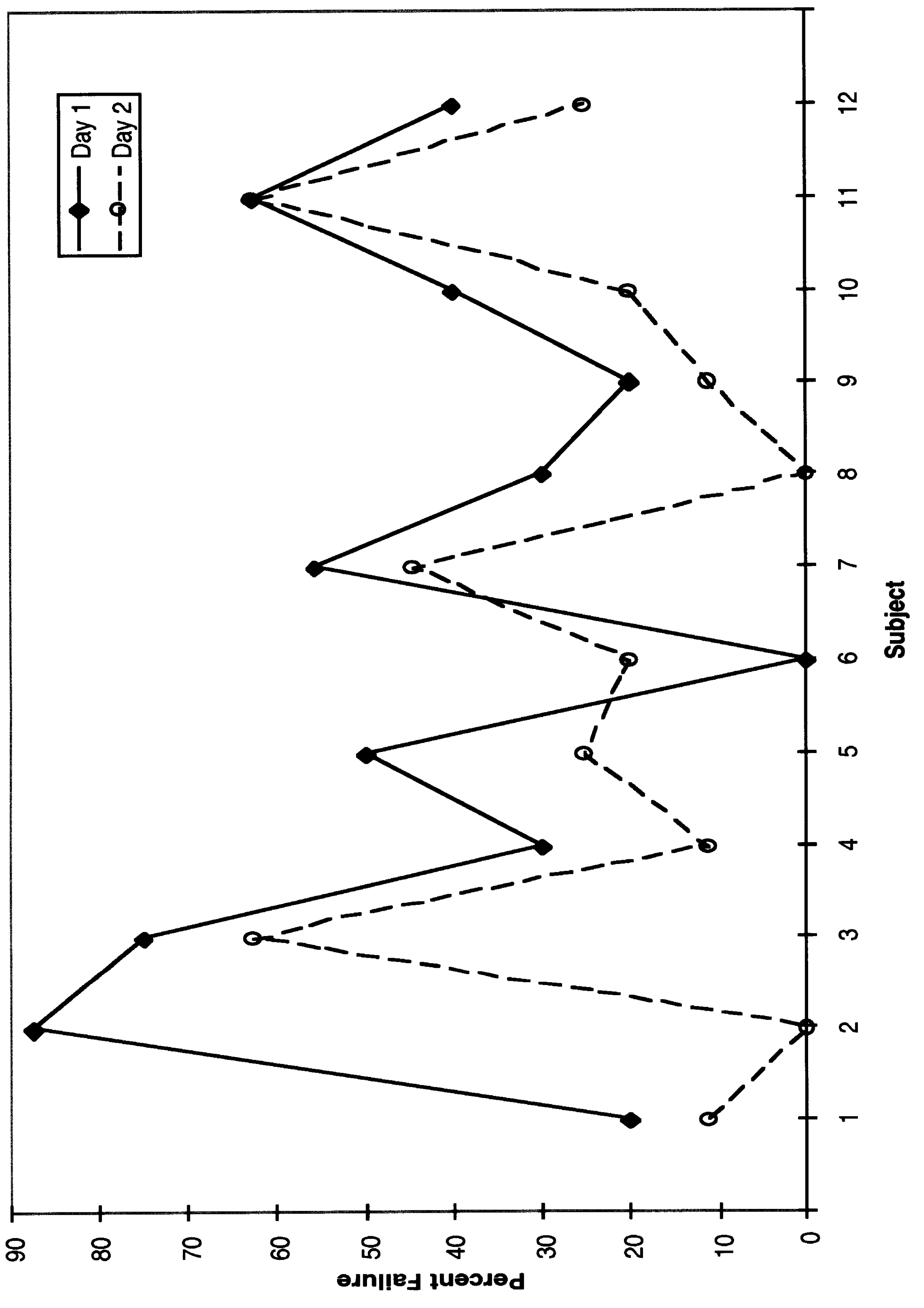


Figure 5.3.1 Percentage of failures in a given day for each subject (normalized to eight trials).

The effect of day is most striking when noticing that the mean percentage of failures across all subjects decreases by nearly one half from day one to day two. Table 5.3.1 shows the number of failures for trials performed with tactile cues relative to the number of total failures in a given day for each subject, the data are plotted in Figure 5.3.2 for both days. For example, subject 3 had a total of 6 failures on the first day, and three of those occurred during tactor trials.

Table 5.3.1 Number of tactor trial failures relative to total number of failures.

Subject	1	2	3	4	5	6	7	8	9	10	11	12
Day 1	2/2	3/7	3/6	2/5	1/3	2/4	0/0	3/5	1/3	1/2	2/4	1/5
Day 2	0/1	0/0	2/5	1/1	2/2	2/2	1/4	0/0	0/1	1/2	2/5	0/2

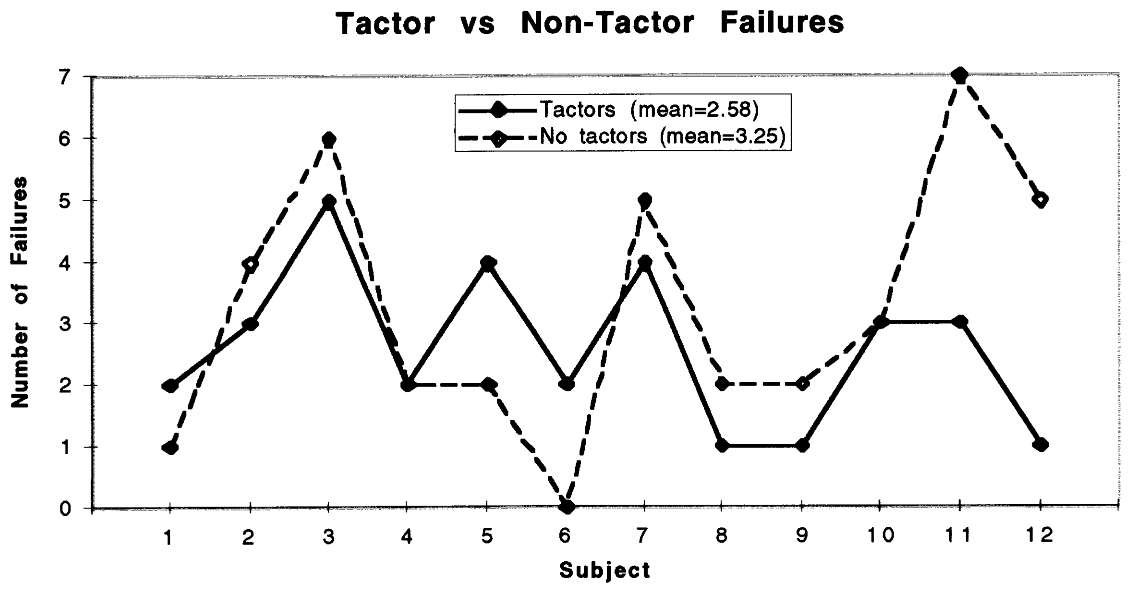


Figure 5.3.2 Number of failures with and without tactors for each subject.

Figure 5.3.2 reveals that significantly fewer failures occur during trials conducted with tactile cueing (n=8, F=10.565, p=0.017). In addition, whereas the number of failures decreased significantly (n=24, F=5.420, p=0.029) from day one to day two, the percentage of those failures attributed to tactor trials remained nearly the same for each day. During both sessions less than half (20 out of 45 for day 1 and 11 out of 25 for day 2) of the failures occurred during tactor trials, 44% for both sessions. This result suggests that the TLS assists the user consistently even in the presence of learning or fatigue effects. In other words, TLS utility does not decrease although the user may be learning throughout the experiment.

Figure 5.3.3 shows the effect of tactile cues on the number of failures as a function of the scene (path-sense code).

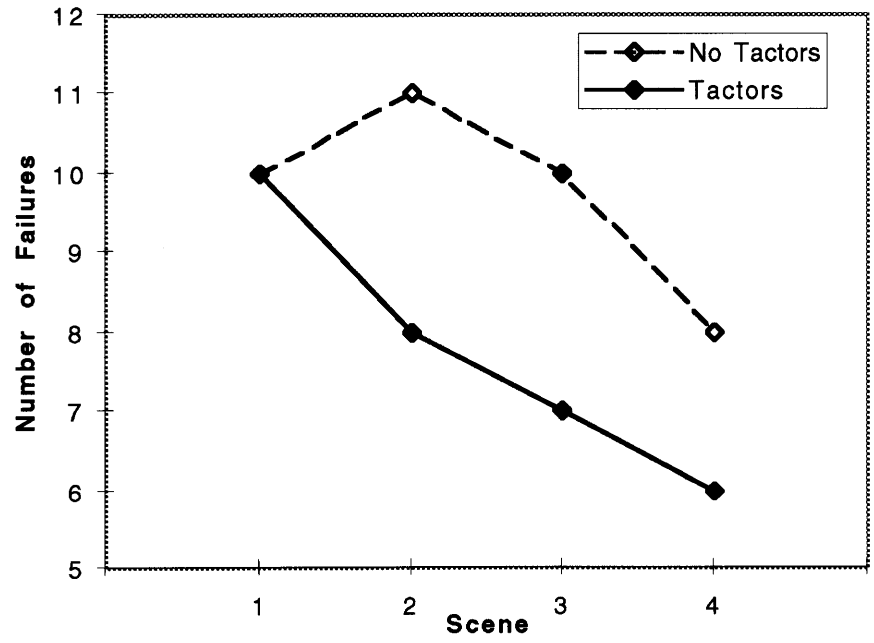


Figure 5.3.3 Number of failures for a given scene for both tactor and non-tactor trials.

Surprisingly, as the scenes *increase* in difficulty, the number of failures *decrease* (not significantly) for both tactor and non-tactor trials. Perhaps the most interesting interpretation of the above result can be seen by plotting the effect of tactors versus scene, shown in Figure 5.3.4.

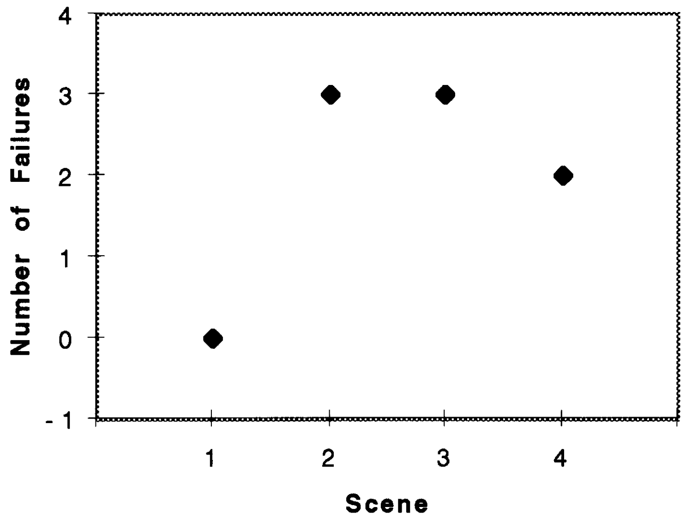


Figure 5.3.4 The effect of tactors on the number of failures for a given scene.

There is no difference in the number of failures for scene one between tactor and non-tactor trials, it therefore acts as a control condition. Recall that this is the only scene where the target is visible at the outset, therefore the scene requires no visual learning and as expected, the tactors have no effect. For the remaining scenes, tactors assist the user by reducing the number of failures as the paths increase in difficulty.

5.4 Discussion

The following section discusses the results presented above. The effect of the Spaceball 3003 is explained in the context of data analysis as well as subjective questionnaire comments obtained from subjects after completing the experiment. Finally a discussion of the impact and conclusions drawn from the main and cross effect statistical analysis is presented.

5.4.1 Input Device Effects

The impact of the input device is apparent because of the large day effect for MT. As the experiment progressed within a day, and from session to session, subjects gained more practice using the input device and were able to tune their control strategies. Although not significant, subjects did maneuver on average forty seconds faster on the second trial day. This suggests that subjects may require more training with the spaceball before experimental data is gathered. Simply the presence of failures suggests that the input device was difficult to control, and this is supported by the significant drop in the total number of failures occurring on the second day; as the subjects became more familiar with the device.

A subjective questionnaire submitted to the subjects two months after the experiment was completed reveals subjects' thoughts regarding the input device and other aspects of the experimental protocol. Table 5.4.1 highlights some subject comments from the questionnaire.

Table 5.4.1 Subjective questionnaire responses.

Device	"[spaceball] really needs some sort of feedback to inputs" "I tried to use translation more than rotation because it was easier to stay oriented" "I wish it had a reference indicator...had a hard time inputting a pure rotation or translation...would have liked [one] for each hand - one to do rotations, one to do translations." "it would be easier if there was some way of switching between translation mode and rotation mode." "no physical feedback present to indicate how the [space] ball is responding"
Strategy	"I got worse on day 2 because I tended to fly faster (get cocky) which made it easier to lose control" "[strategy] changed from the first day to the second - the first day I was more willing to rotate, the second I tried to avoid it at all costs" "The general strategy was the same [from day 1 to day 2]" "My strategy was pretty much the same once I'd figured out how to fly during the practice runs" "day one: was trying to follow the 'instructions' from the tactors. day two: listened to the tactors but whenever possible tried to turn so that I could see the target" "I learned that 'less was better'"
Trials	"however many trials we did in a day was way too many" "shorter runs - got pretty tired"

Tactors	"very useful before I could see the target" "maybe having the vibrators vibrate at different amplitudes so that when you are getting close to an intended point, the vibrator eases down to a lower amplitude" "no indication of distance (i.e. pulsing for short distances, continuous for long" "I think [tactors] helped a lot. I would have liked a more 'violent' stimulus..." "pretty easy to get used to" "when the [partner] astronaut was hidden by the station, I flew 'completely on instruments', using just the tactors. Need more power in the tactors." "The vibrotactile stimuli seem like a good source of navigational information." "the difficulty of using the spaceball probably obscured some of the effects, but the tactile simulation was useful, especially when the target was out of view.
Scenes	"it was possible to learn the scenario and then optimize your strategy the next time it came around" "The trials where the target was not visible from the starting position were more difficult, until you learned the location of the target and route to it based on what the starting position looked like"

Each subject mentioned first that it was more challenging to control rotation than translation. Within the Lynx program, it was possible to vary the sensitivity of the spaceball to both translation and rotation individually, however, even when the sensitivities were the same, subjects reported that the spaceball felt more responsive to rotations. Specifically, to input a pure rotation was difficult because of the coupling of the two modes, therefore subjects tried to keep rotations to a minimum. While the SAFER unit that the ISS astronauts will use also employs a single input device, the translation and rotational modes cannot be activated simultaneously. The astronaut can toggle between the two modes of operation using a simple switch. Conducting the experiment with a similar device might alleviate the day effect, number of failures and reduce movement times overall, allowing for more trials and isolating the tactor effects more completely. Many subjects chose to align themselves 'upright' with the target (as soon as it was in view) through a series of rotations first, then travel the remaining distance to the target using a series of translational movements. The subject is therefore trying to increase her SA by maneuvering to a familiar orientation to more easily attain level 3 SA (projection to a future state). Loss of control was typically a result of having to recover from an overcorrection in rotation or high velocity translation, so that in the absence of large damping and with the coupled control dynamics, it was difficult to predict future behavior (attain level 3 SA) and determine the appropriate amount of counter correction to apply. Subjects also complained the lack of feedback, and of fatiguing during the trials, as was seen in section 5.2 Subject Effects. Perhaps a better method of training subjects with the spaceball would be to increase the number of trial days, decrease the number if trials in a given session, and begin experimental trials only on the final days of the experiment.

5.4.2 The Effect of Tactors

The advantageous effect of tactors demonstrates that the TLS improves the SA of the user by allowing her to react faster to an unfamiliar situation, as well as maneuver to a target more quickly and efficiently. In addition, because the TLS offers consistent savings from day to day, its utility does not decrease with subsequent uses, and may be independent of the amount of training or prior experience the user has with the system. Clearly the TLS elicited significant effects on the first trial day even as subjects were still acclimating to the spaceball device. This is not surprising however, as the TLS is designed to intuitively increase the SA of the user in an unfamiliar situation.

The day effect on RT (faster response times on the second day) most likely results from subjects recognizing scenes from the previous trial day. Although scenes were presented twice in a trial day, recognition did not occur until the second day. The effect of sense is interesting in that although sense 0 was designed to be easier than sense 1, subjects took longer to react to sense 0 scenes (recall that there are two paths, one straight line path (path 0) and one indirect path (path 1) and each path can be traversed in two (opposite) senses, sense 0 (forward) and sense 0 (in reverse)). This is a direct consequence of the non-tactor scene 3 (path 1, sense 0) trials where the ISS (but not the target) was visible at the outset, and the subject was required to orient herself in the absence of tactile cues in order to interpret the verbal cue as to the targets location. This is confirmed by the cross effect of sense and tactor that shows that tactile cueing assists more with sense 0 than sense 1, where the subject's SA is increased by the tactile information. Clearly in an emergency situation where an astronaut must quickly discern her position relative to her destination (that may not be immediately visible), the increased SA (particularly level 1- perception of the elements in the environment, and level 2 -comprehension of the current situation) afforded by the TLS can be critical.

Since scene 1 (path 0 sense 0) was the only scene where the target was visible at the outset, it provided a control for measuring the extent to which the TLS complements the visual system. Although the experiment was not designed to collect data on the frequency and situations under which subjects were attentive to the tactile cueing, comments suggest that the tactile cues were most useful when the target was not in view, and when control corrections needed to be made, even when the target was visible.

The following chapter Summary and Conclusions, offers a summary of the thesis, conclusions drawn from the experiment conducted and suggestions for future research in the context of improvements to the current experimental protocol.

6. SUMMARY AND CONCLUSIONS

This thesis experimentally verifies the utility of a new technology that could become a great asset to the space program. It is widely recognized that there exists a problem with disorientation in space. For Space Shuttle missions, this is largely resolved with costly training programs and extended mission times, as astronauts must adapt to the weightless environment before reaching their full performance capability. These problems will only escalate with the construction of the ISS, numerous EVA's are required at the outset, and the current practice of delaying EVA's until after the first three days of flight could significantly add cost to the program not only monetarily, but in terms of lost mission time and extended resources. Chapter one, Introduction, the motivation for a new type of display to increase an astronaut's SA is presented. A comparison is drawn between the current Space Shuttle program and the ISS program, demonstrating the increased demand that will be placed on EVA system requirements (i.e. safety, reliability, cost, etc.). The contribution and goal of the thesis is stated, to investigate a display to that will assist astronauts to gain SA in disorienting circumstances, and maintain SA as they maneuver about the ISS.

In personal communication, US astronaut John Blaha after returning from a 4 month stay on the Russian space station MIR remarked (in regard to spatial orientation) that in-flight it took approximately one month before finding your way around was natural and instinctive. He went on to explain that the relative 3D orientation of the modules was not clear and in general felt that he could not have pointed correctly to another module - even by the end of the flight [Blaha1997]. As mentioned in the previous chapter, the utility of the TLS does not decrease with time and therefore astronauts who continue to have spells of SD throughout the flight could benefit consistently from the vibrotactile cues provided by the TLS until the end of the mission. Also, astronaut Blaha mentioned that the Shuttle astronauts arriving on MIR to retrieve her appeared disoriented and he was concerned that this early disorientation could prove to be hazardous in the case of an emergency. For example, in an emergency evacuation, the Shuttle astronauts would not know which way to turn, or the path to get out [Blaha, 1997]. Equipping astronauts with the TLS during this time could be useful, as of course the display can be used for IVA as well as EVA.

Chapter two discusses the background of how the human perceives her surrounding to form a model of her current state. The burden on the visual system to perform primary tasks as well as compensate for other sensory channels not operating at their full potential, motivates the use of the skin receptors for the display to complement the visual system. The TLS is introduced and the static and dynamic capabilities of the display are discussed. Research has shown that the skin has a high information capacity and its phenomenon such as the phantom sensation, enhancement and summation, make it particularly well suited for both static and dynamic information transmission. Furthermore, tactile stimulation elicits a reflexive and intuitive response. That the TLS is intuitive is perhaps its greatest asset. In any emergency situation where time is critical, an aid or display that requires significant processing or interpretation is unsatisfactory and could potentially be more harmful than useful. Finally in chapter two, an overview of a potential self-contained navigation solution that would be required to run the TLS hardware is presented, along with recommendations for EVA applications, including DGPS.

Chapter three outlines the pilot study and results which drove the design for the ISS EVA experiment. The study tested and quantified (measuring reaction times and errors) subjects ability to resolve one, two and three vibrotactile stimuli from the TLS, into a directional vector in space. Results demonstrate that as the number of stimuli increase, so do reaction times and numbers of errors. However, no changes were made to the TLS configuration for the ISS EVA experiment. Subjects commented that during the ISS experiment that when they focused on the tactile stimulus, it was to gain a general sense of direction to the target rather than its exact location 1) when the target was still a considerable distance away and/or not in view and 2) during higher velocity translations and rotations when the tactor patterns were changing rapidly. The results also showed that the auditory control stimulus garnered shorter reaction times than the vibrotactile stimulus, most likely as a result of insufficient training with the TLS.

Chapter four presents the ISS EVA experimental methods detailing the ISS task scenario, hardware, software and subject information. The protocol and data analysis methods are also presented. Twelve subjects, six men and six women ranging in age from 21 to 27, took part in the experiment over a series of two trial days. Subjects completed a computer simulated target acquisition task with and without the use a the TLS vibrotactile display in order to asses its ability to decrease reaction and movement times. The simulation controller is a six degree of freedom input device whose dynamics and sensitivity represented motion in microgravity. The protocol is designed to yield repeated measures for the various trial conditions. Variables include modality (tactors or no tactors), path, sense, day and gender. The scenes are designed to vary the level of difficulty of the tasks with one scene acting as a control for the remaining three by placing the target within the visual range of the subject at the outset of the trial.

The results chapter presents and discusses the outcome of the data analysis. Results show that the TLS is an effective way to reduce reaction times and movement times by providing cues as to the user's position and orientation. Tactile cueing was shown to significantly save the subject an average of 92 seconds of movement time (time to acquire the target), and 4.5 seconds of reaction time. The cross effect and main effect of sense is only significant for reaction times, indicating that some scenes were more difficult at the outset than others. The day also contributes significantly to reaction time (with decreased times on day two) arguing that subjects recognized scenes from the previous trial day and therefore required less time to determine an initial movement direction. Failure analysis and learning effects reveal that fewer failures occur on the second day of testing and that some subjects demonstrate continued improvement in movement times (although not significantly). Failures were a result of loss of control using the spaceball input device which suggests that subjects require more training before experimental data are recorded. The 92 seconds of movement time saving mentioned above is solely a result of a main tactor effect and demonstrates that the user had increased SA during tactor trials. Statistically there were no other significant main or cross effects contributing to these savings other than the tactile stimulus itself. The increase in SA that this vibrotactile display provides has the potential to decrease the cost in terms of fuel, time and complexity of not only a self-rescue, but of general translation tasks, increasing the overall safety and efficiency associated with moving about the ISS.

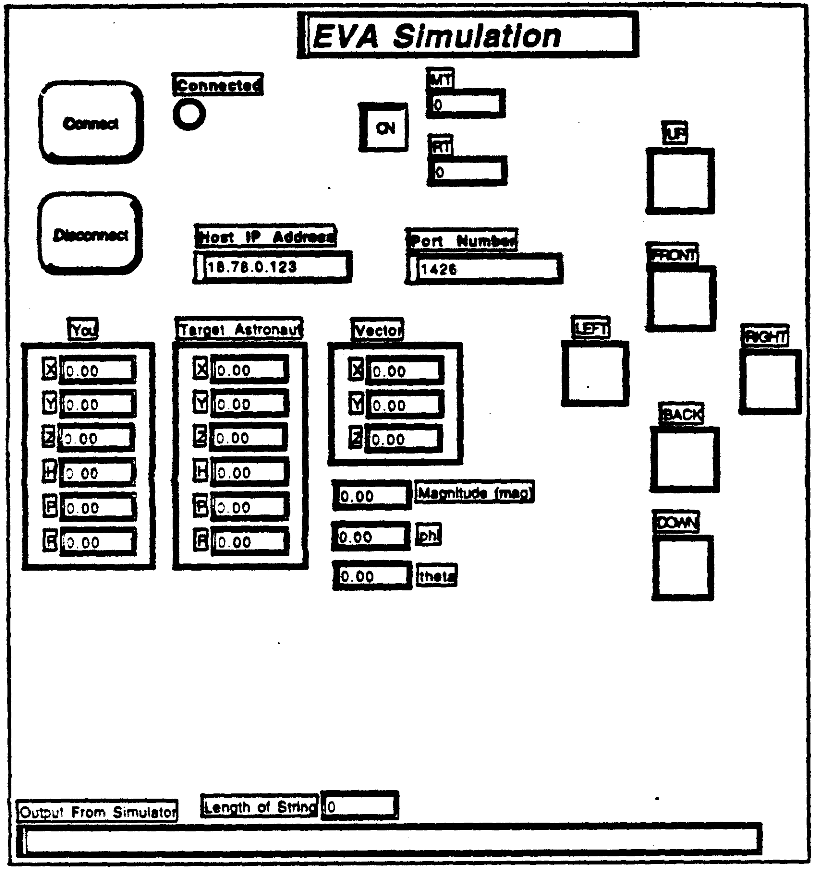
To further explore this technology, I would recommend changing the input device to one that is more representative of the one found on the SAFER unit and perhaps incorporate an element of force feedback as per subject's suggestions. Increasing the number of tactors would increase the resolution of position that was available to the user, and provide a greater sense of flow across the body, rather than discrete stimuli. Adding rate information through varying frequency pulses would provide a control movement cue to the user, for example, increasing the frequency of the tactor pattern as the target grows nearer. As a result, in addition to the direction to the target, the user has an indication of the closing distance to the target and can interpret this as the appropriate magnitude of control to input.

As discussed in Chapter 2, Background, velocity or motion information is a necessary part of discerning one's position and orientation, and therefore one's SA. In this experiment, the TLS was being tested solely as a position aid where the distance to the target screen display served to complete the user's SA by providing rate (flow) information. However, it was an indicator which required visual attention to be drawn from the primary target acquisition task. Incorporating velocity information into the TLS is a necessary next step to maximize its effectiveness and value by ensuring that all of the information necessary to attain complete SA are supplied within the system.

Perhaps the hidden importance of the TLS is that it is well suited in an abundance of circumstances, above and beyond ISS situations. A device that acts as a navigator, target identifier and emergency safety device can be used by astronauts exploring other planets, underwater civilian and military divers, pilots for both general aviation and combat scenarios, persons with visual disabilities, and of course for the plethora of teleoperation and human supervisory applications. Imagine the benefit of wearing such a device for remote sensing. Operating a remote explorer vehicle such as a planetary rover for example, the user would be experiencing and sensing the movements of the vehicle intuitively as if she were moving about herself, able to react to obstacles while mapping new terrain.

The need for and benefit of the TLS is clear. As a next step, testing this equipment in a neutral buoyancy tank while wearing a pressurized EVA suit would provide simulated microgravity conditions where response to unusual orientations could be studied. Understanding the mechanisms by which a human navigates and recovers from unusual orientations in general and under emergency conditions, could assist in not only astronaut training and with the design of the most effective and intuitive astronaut aid for the ISS, but also in producing a breakthrough SA aid with countless prospects.

APPENDIX A: LAB VIEW PROGRAMS



MT 0

RT 0

Host IP Address 18.78.0.123

Port Number 1426

You		Target Astronaut		Vector	
X	0.00	X	0.00	X	0.00
Y	0.00	Y	0.00	Y	0.00
Z	0.00	Z	0.00	Z	0.00
H	0.00	H	0.00		
P	0.00	P	0.00		
R	0.00	R	0.00		

0.00 Magnitude (mag)

0.00 phi

0.00 theta

Output From Simulator

Length of String 0

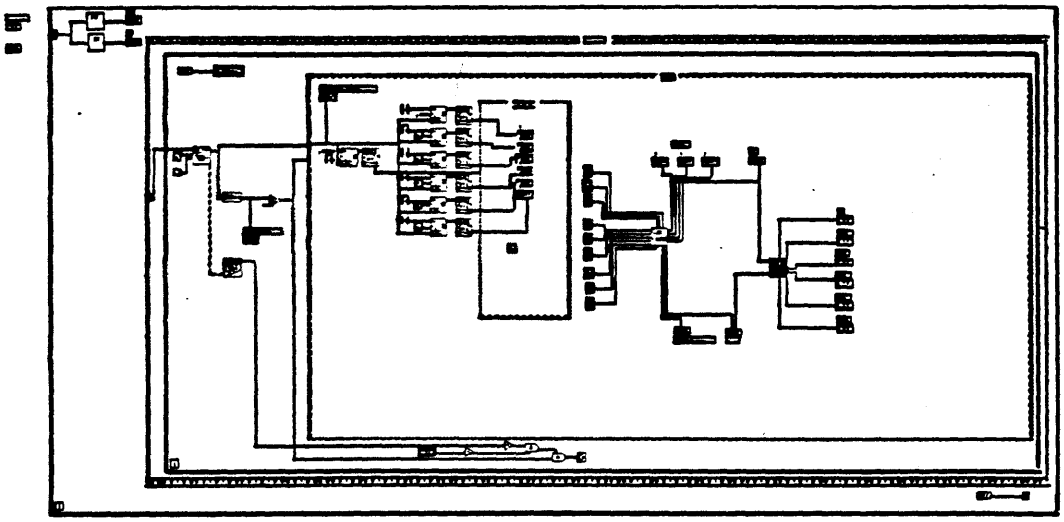
TF	
TF	
abc	Host IP Address
abc	Port Number
TF	
abc	
TF	Connected
EXT	X
EXT	Y
EXT	Z
EXT	H
EXT	P
EXT	R
EXT	X
EXT	Y
EXT	Z
EXT	H
EXT	P
EXT	R
EXT	X
EXT	Y
EXT	Z

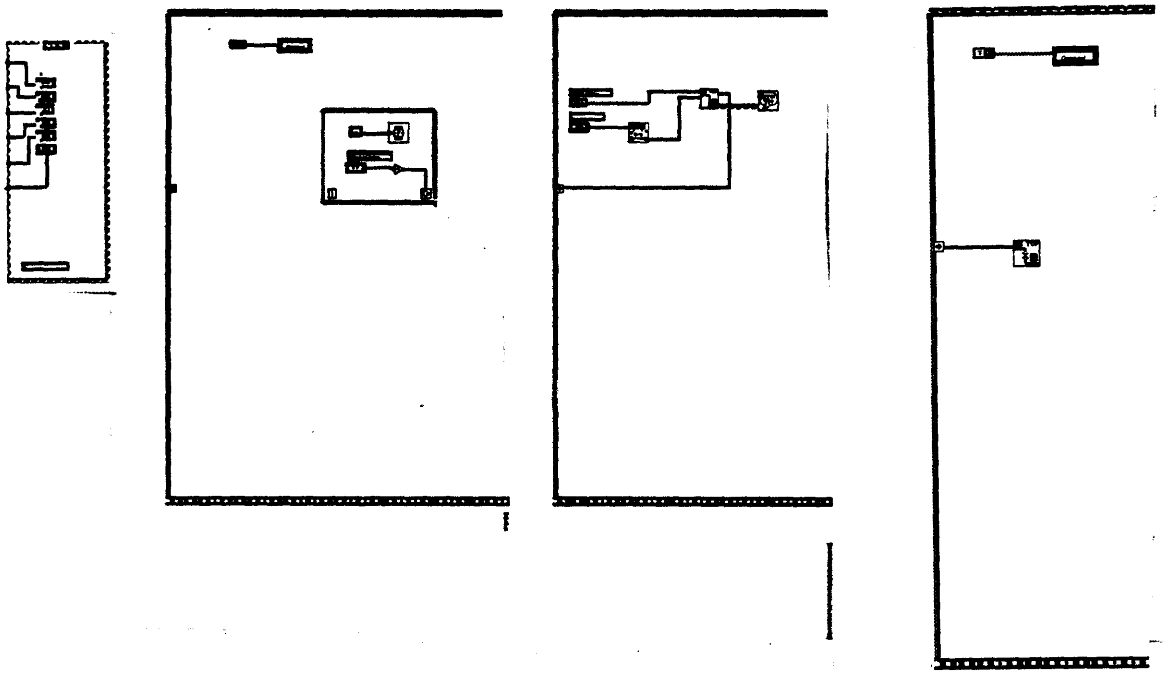
abc	Output From Simulator
I32	Length of String
EXT	Magnitude (mag)
EXT	phi
EXT	theta

TF	UP
TF	FRONT
TF	LEFT
TF	BACK
TF	RIGHT
TF	DOWN

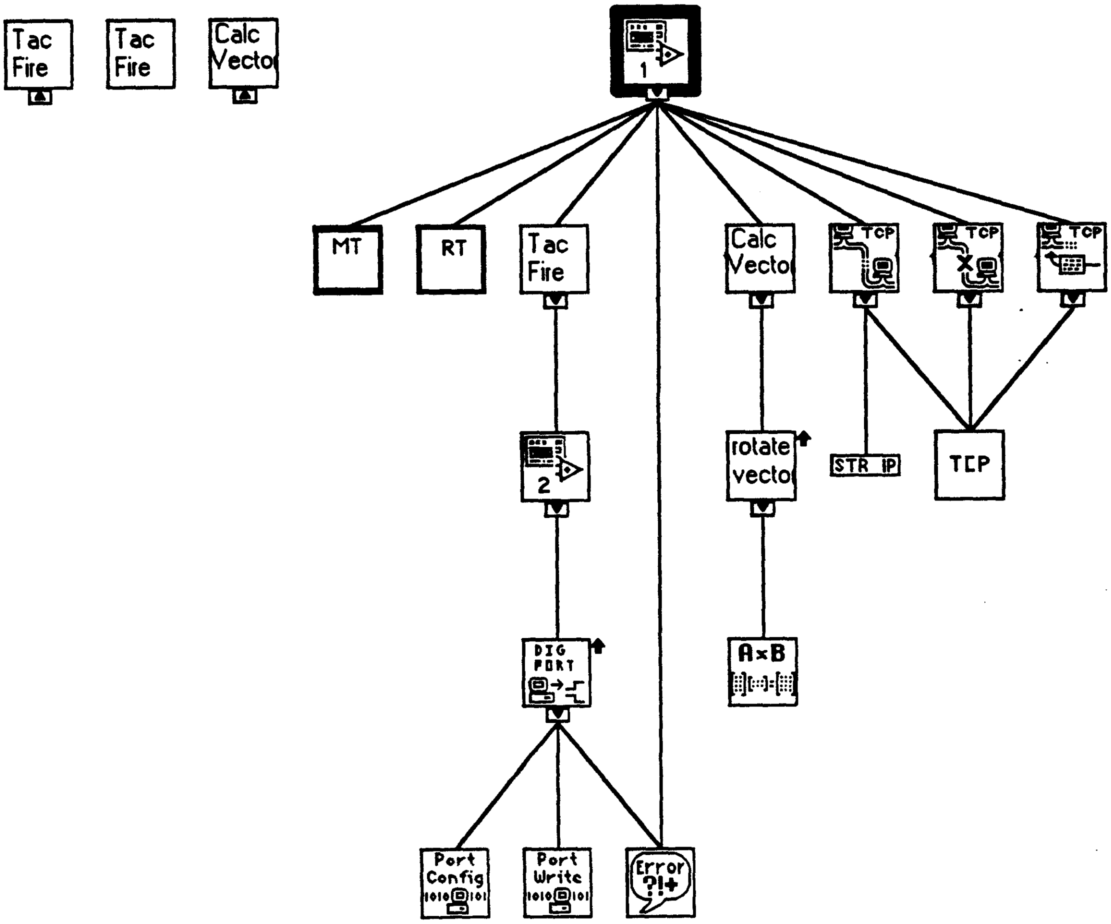
U32	RT
U32	MT

Block Diagram

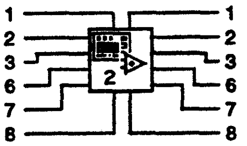




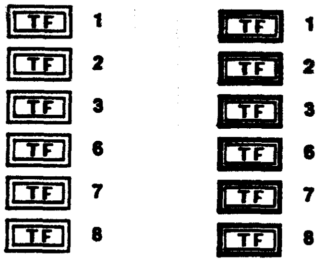
Position in Hierarchy



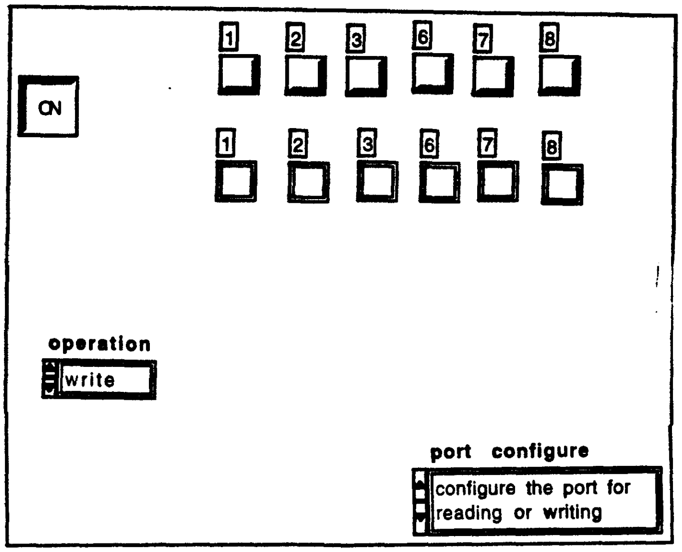
Connector Pane

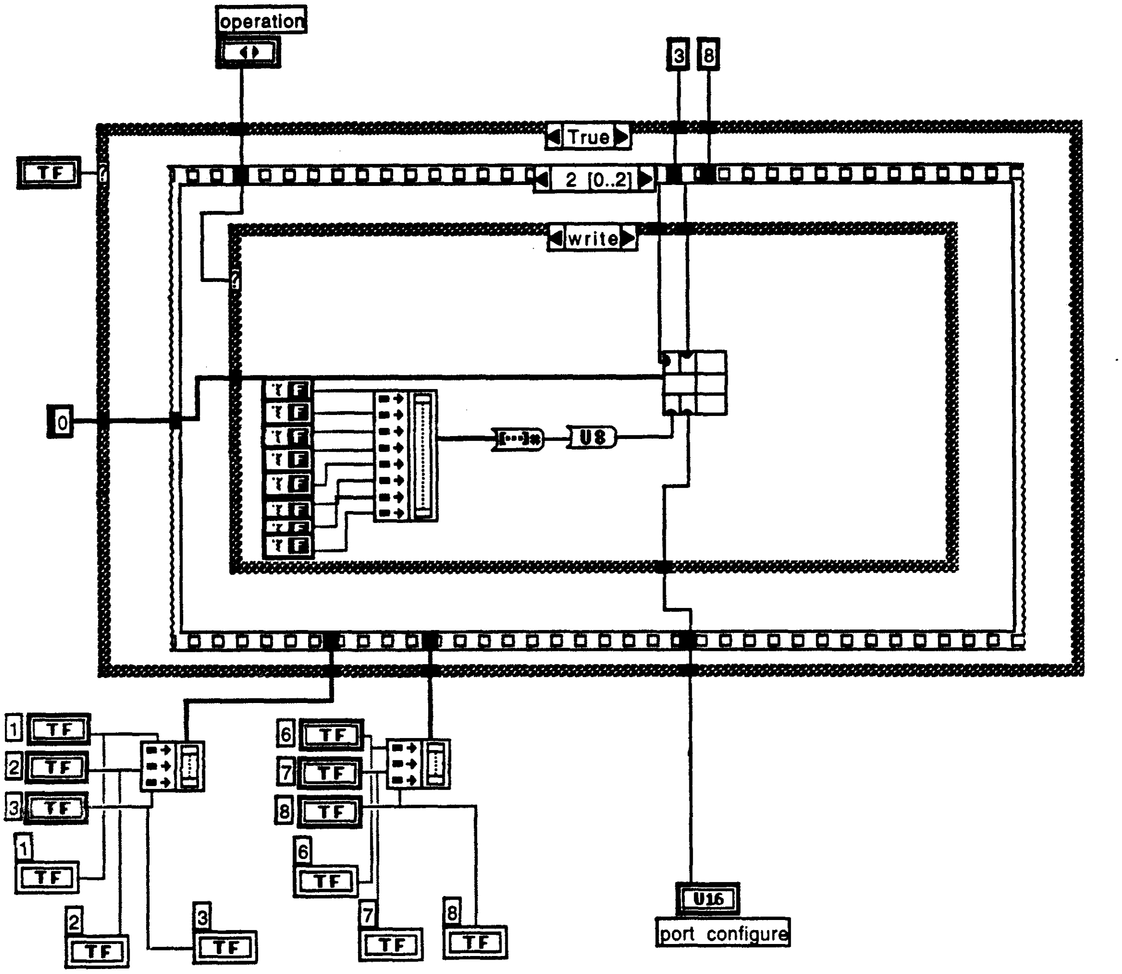


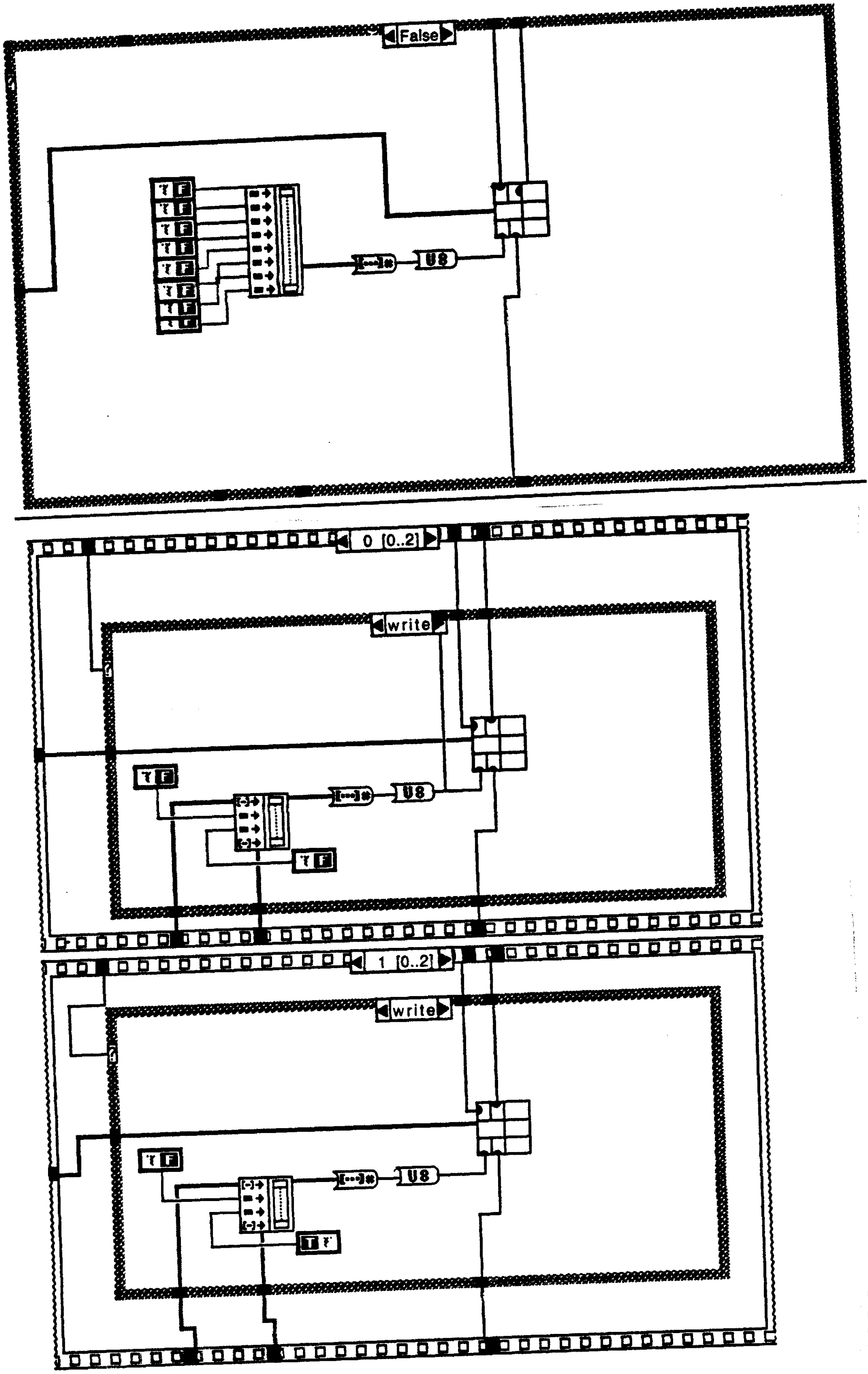
Users:Jen:VI's:tactor:trythis.vl

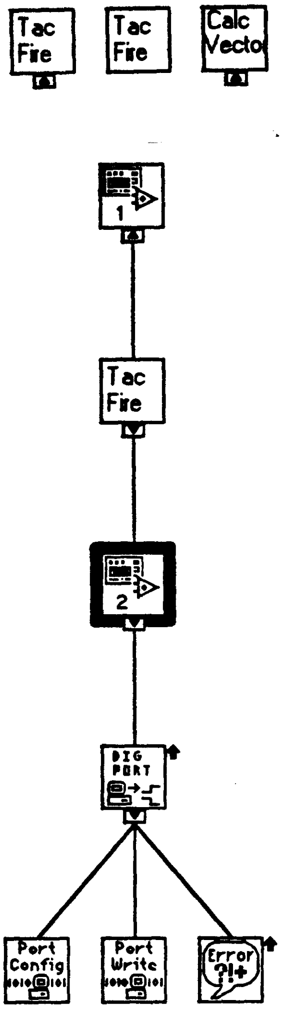


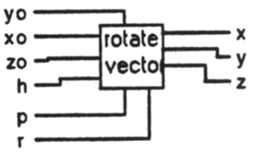
Front Panel






False
U8
0 [0..2]
write
U8
1 [0..2]
write
U8


Tac Fire
Tac Fire
Calc Vecto
1
Tac Fire
2
DIG PORT
Port Config
Port Write
Error ?!+



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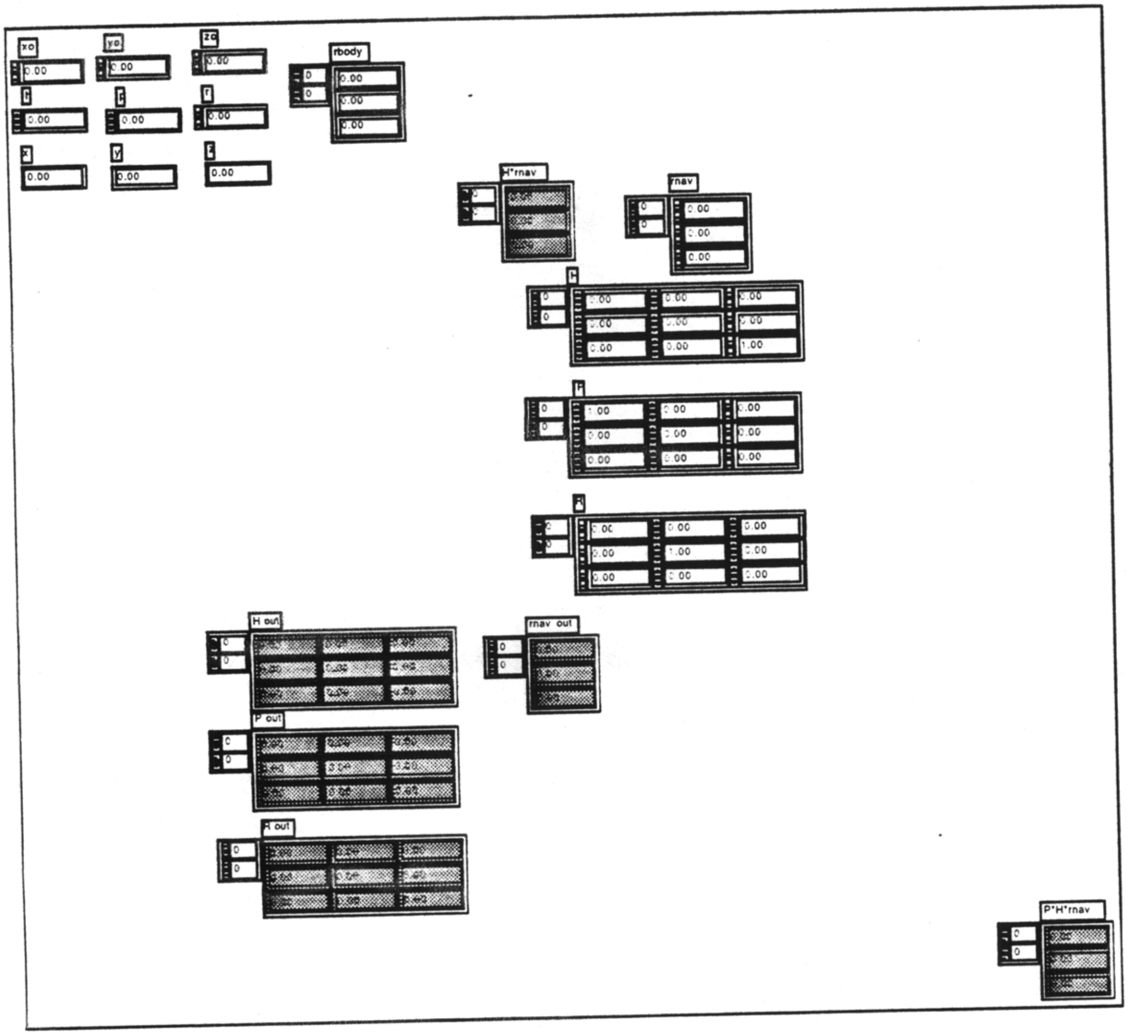


Controls and Indicators

EXT h

EXT p

EXT r

EXT xo

EXT yo

EXT zo

[DBL] H
DBL

[DBL] P
DBL

[DBL] R
DBL

[DBL] rnav
DBL

EXT x

EXT y

EXT z

[DBL] H out
DBL

[DBL] P out
DBL

[DBL] R out
DBL

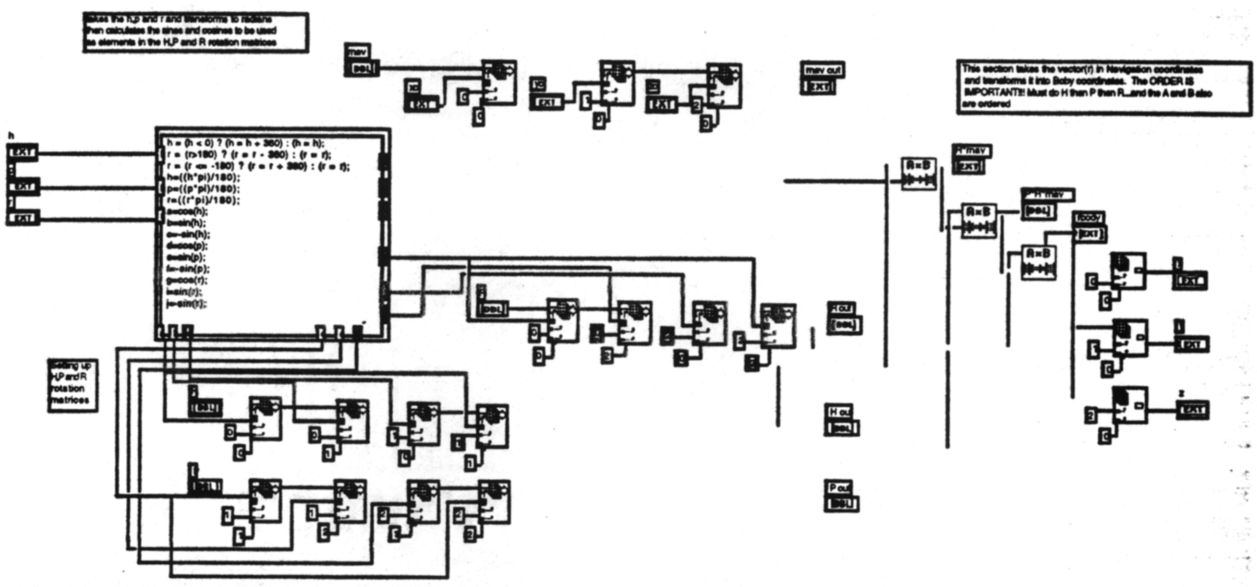
[EXT] rnav out
EXT zo

[EXT] rbody
EXT

[EXT] H*rnav
EXT

[DBL] P*H*rnav
DBL

Block Diagram



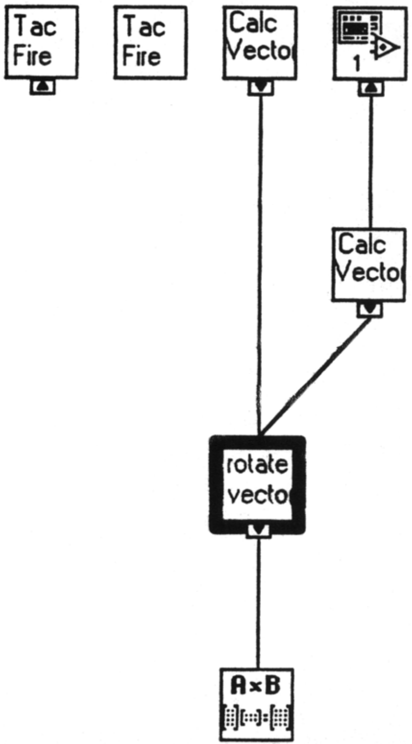
akes the h,p and r and transforms to radians
hen calculates the sines and cosines to be used
s elements in the H,P and R rotation matrices

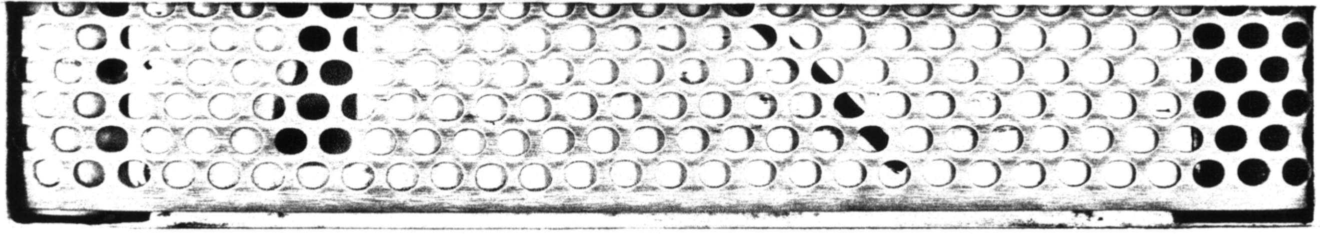
```
h = (h < 0) ? (h = h + 360) : (h = h);
r = (r>180) ? (r = r - 360) : (r = r);
r = (r <= -180) ? (r = r + 360) : (r = r);
h=((h*pi)/180);
p=((p*pi)/180);
r=((r*pi)/180);
a=cos(h);
b=sin(h);
c=-sin(h);
d=cos(p);
e=sin(p);
f=-sin(p);
g=cos(r);
i=sin(r);
j=-sin(r);
```

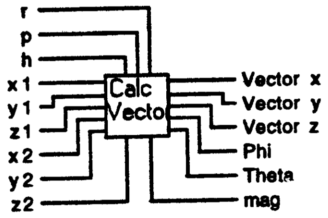
Setting up H,P and R rotation matrices

This section takes the vector(r) in Navigation coordinates and transforms it into Boby coordinates. The ORDER IS IMPORTANT!!! Must do H then P then R...and the A and B also are ordered

Position in Hierarchy







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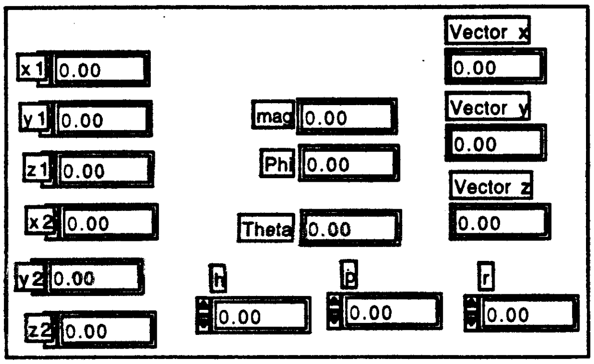
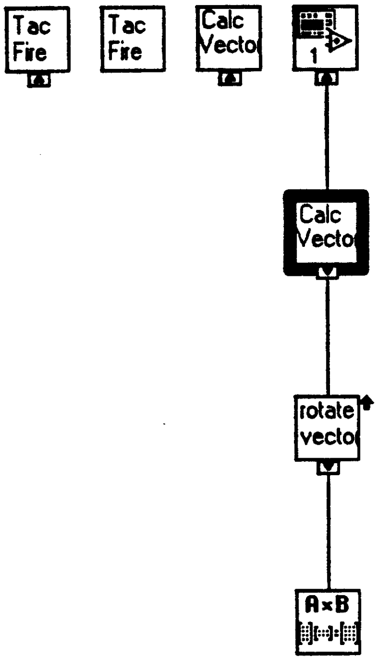


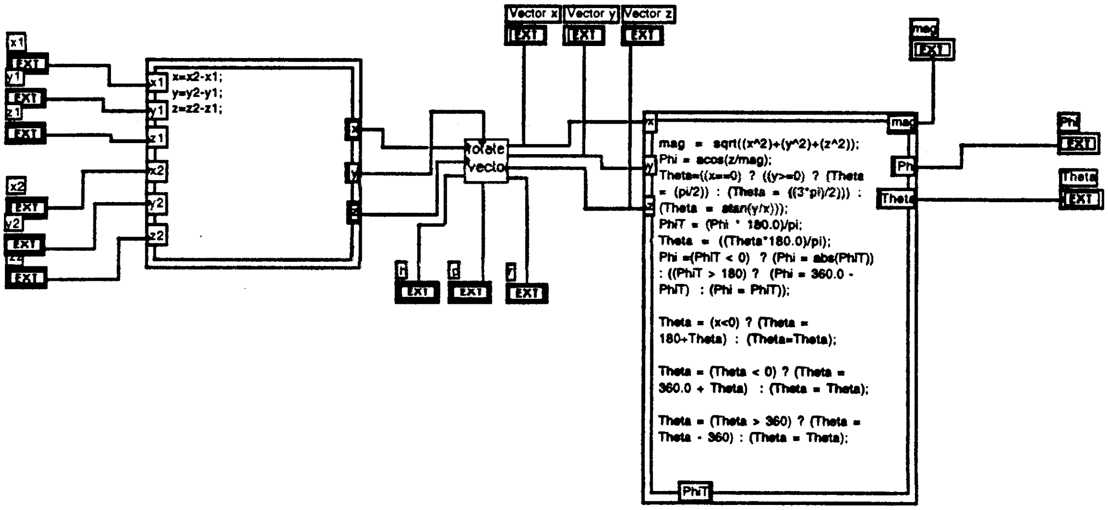
x 1 0.00
y 1 0.00
z 1 0.00
x 2 0.00
y 2 0.00
z 2 0.00
mag 0.00
Phi 0.00
Theta 0.00
Vector x 0.00
Vector y 0.00
Vector z 0.00
h 0.00
p 0.00
r 0.00



Controls and Indicators

EXT x 1
EXT y 1
EXT z 1
EXT x 2
EXT z 2
EXT y 2
EXT h
EXT p
EXT r
EXT **mag**
EXT **Phi**
EXT **Theta**
EXT **Vector x**
EXT **Vector y**
EXT **Vector z**

Block Diagram



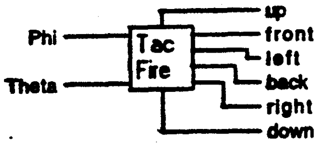
```
x=x2-x1;
y=y2-y1;
z=z2-z1;
```

```
mag = sqrt((x^2)+(y^2)+(z^2));
Phi = acos(z/mag);
Theta=((x==0) ? ((y>=0) ? (Theta
= (pi/2)) : (Theta = ((3*pi)/2))) :
(Theta = atan(y/x)));
PhiT = (Phi * 180.0)/pi;
Theta = ((Theta*180.0)/pi);
Phi =(PhiT < 0) ? (Phi = abs(PhiT))
: ((PhiT > 180) ? (Phi = 360.0 -
PhiT) : (Phi = PhiT));

Theta = (x<0) ? (Theta =
180+Theta) : (Theta=Theta);

Theta = (Theta < 0) ? (Theta =
360.0 + Theta) : (Theta = Theta);

Theta = (Theta > 360) ? (Theta =
Theta - 360) : (Theta = Theta);
```



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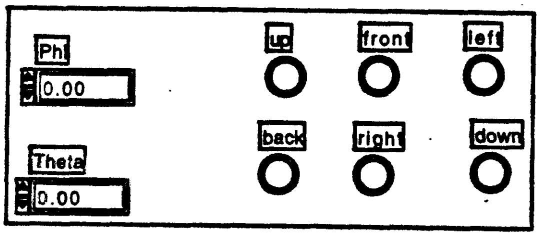
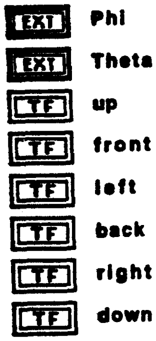
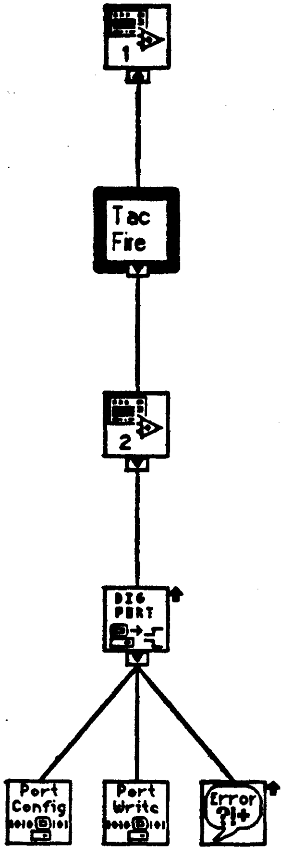
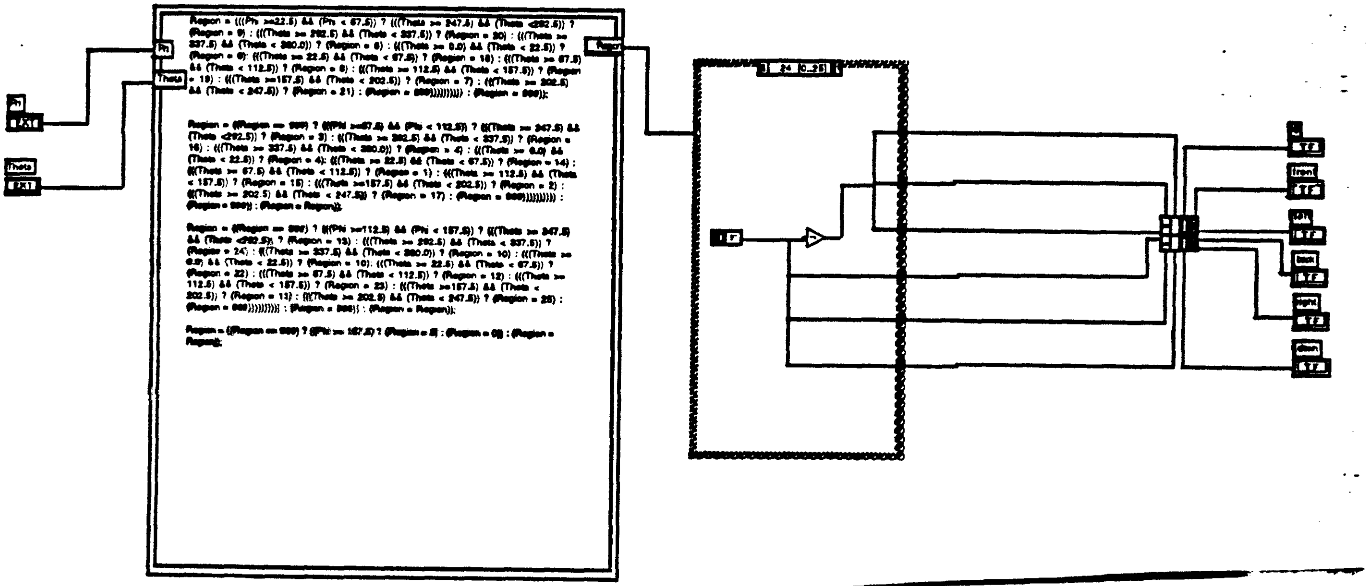






List of SubVIs

trythis.vi



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(Region = 9) : (((Theta >= 292.5) && (Theta < 337.5)) ? (Region = 20) : (((Theta >=
337.5) && (Theta < 360.0)) ? (Region = 6) : (((Theta >= 0.0) && (Theta < 22.5)) ?
(Region = 6): (((Theta >= 22.5) && (Theta < 67.5)) ? (Region = 18) : (((Theta >= 67.5)
&& (Theta < 112.5)) ? (Region = 8) : (((Theta >= 112.5) && (Theta < 157.5)) ? (Region
= 19) : (((Theta >=157.5) && (Theta < 202.5)) ? (Region = 7) : (((Theta >= 202.5)
&& (Theta < 247.5)) ? (Region = 21) : (Region = 999)))))))))) : (Region = 999));

Region = ((Region == 999) ? (((Phi >=67.5) && (Phi < 112.5)) ? (((Theta >= 247.5) &&
(Theta <292.5)) ? (Region = 3) : (((Theta >= 292.5) && (Theta < 337.5)) ? (Region =
16) : (((Theta >= 337.5) && (Theta < 360.0)) ? (Region = 4) : (((Theta >= 0.0) &&
(Theta < 22.5)) ? (Region = 4): (((Theta >= 22.5) && (Theta < 67.5)) ? (Region = 14) :
(((Theta >= 67.5) && (Theta < 112.5)) ? (Region = 1) : (((Theta >= 112.5) && (Theta
< 157.5)) ? (Region = 15) : (((Theta >=157.5) && (Theta < 202.5)) ? (Region = 2) :
(((Theta >= 202.5) && (Theta < 247.5)) ? (Region = 17) : (Region = 999)))))))))) :
(Region = 999)) : (Region = Region));

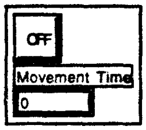
Region = ((Region == 999) ? (((Phi >=112.5) && (Phi < 157.5)) ? (((Theta >= 247.5)
&& (Theta <292.5)) ? (Region = 13) : (((Theta >= 292.5) && (Theta < 337.5)) ?
(Region = 24) : (((Theta >= 337.5) && (Theta < 360.0)) ? (Region = 10) : (((Theta >=
0.0) && (Theta < 22.5)) ? (Region = 10): (((Theta >= 22.5) && (Theta < 67.5)) ?
(Region = 22) : (((Theta >= 67.5) && (Theta < 112.5)) ? (Region = 12) : (((Theta >=
112.5) && (Theta < 157.5)) ? (Region = 23) : (((Theta >=157.5) && (Theta <
202.5)) ? (Region = 11) : (((Theta >= 202.5) && (Theta < 247.5)) ? (Region = 25) :
(Region = 999)))))))))) : (Region = 999)) : (Region = Region));

Region = ((Region == 999) ? ((Phi >= 157.5) ? (Region = 5) : (Region = 0)) : (Region =
Region));
```

Connector Pane

RT.vi

Front Panel

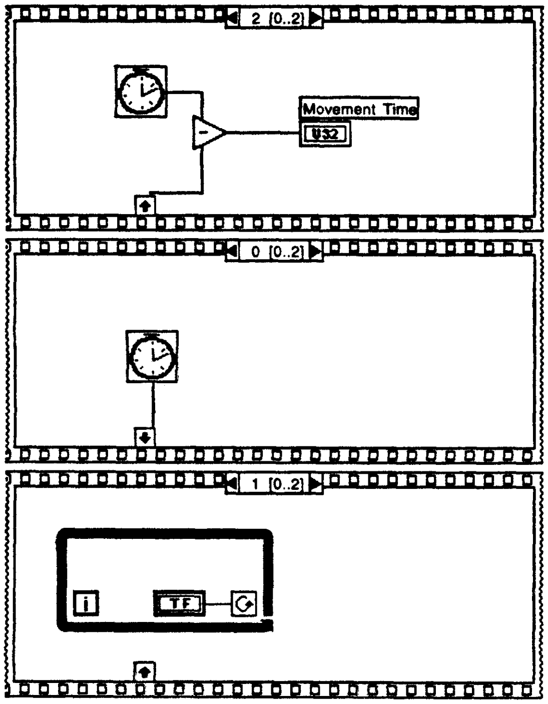


Controls and Indicators

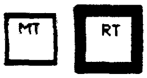
TF

U32 **Movement Time**

Block Diagram



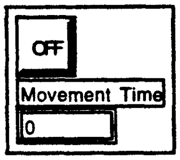
Position in Hierarchy



Connector Pane

MT.vi

Front Panel

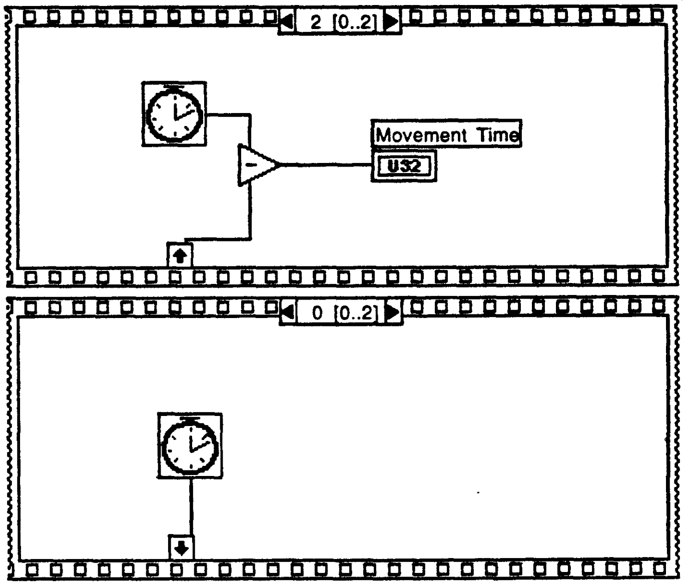


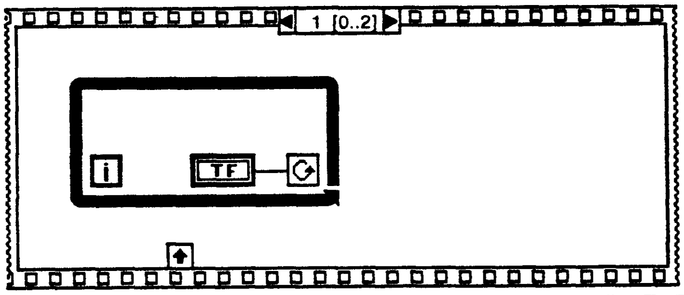
Controls and Indicators

TF

U32 **Movement Time**

Block Diagram





APPENDIX B: INFORMED CONSENT FORM

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MAN-VEHICLE LABORATORY

A VIBROTACTILE DISPLAY FOR AIDING EXTRAVEHICULAR ACTIVITY (EVA) NAVIGATION IN SPACE

SUBJECT CONSENT FORM
COUHES Application No. 2372

I have been asked to participate in a study designed to test a vibrotactile display's ability to act as a navigation aid to astronauts during a time critical task. I understand that participation is voluntary and that I may withdraw consent and discontinue participation at any time for any reason.

I understand that this experiment will be conducted in the Man-Vehicle Laboratory at MIT. I will be seated at a Silicon Graphics Inc. workstation, responsible for displaying the simulation graphics. I will don the Tactor Locator System, a vest containing six small electromechanical speakers distributed over the torso. The resulting sensation of each tactor will be no stronger than a conventional cellular pager motor. Each of the six tactors will represent one of the following directions in space relative to my torso; Up, Down, Right, Left, Front, Back. At this time, I will be allowed to practice resolving the given vibrotactile stimuli into a directional vector, indicating the location of a target. I will then be introduced to the input device, the "Spaceball 3000", that allows me to maneuver about the on-screen scenario in six-degrees of freedom. I will be allowed to train with the input device by maneuvering through a "virtual town", much like playing a video arcade game, until becoming accustomed to the dynamics of the spaceball. Once I feel comfortable with the device I will be given additional time to practice maneuvering throughout the town with the tactor stimuli activated so that I can again practice resolving the directional vector to a target, while I am in "motion" on the screen.

Once the training has been completed, the experimenter will explain to me the International Space Station scenario and task. There will be a total of sixteen experimental trials, eight with the tactile stimulus activated and eight without. My movement time and reaction time will be recorded.

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the MIT Medical Department, including first aid emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available, or providing it, does not imply that such injury is the investigator's fault. I also understand that by my participation in this study I am not waiving any of my legal rights. (Further information may be obtained by calling the Institute's Insurance and Legal Affairs Office at 253-2822.)

I understand I will receive no compensation for participating in this experiment and that I may receive answers to any questions related to this experiment by contacting the Principal Investigator at (617) 258-8799.

I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, H. Walter Jones, Jr. M.D. (MIT E23-389, 253-6787), if I feel I have been treated unfairly as a subject.

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

Subject Name (Print)____________________________________

Subject signature_______________________________________
Date ___________

Experimenter ____
Date ___________

APPENDIX C: DATA

C1: PILOT STUDY DATA

SUBJECT	TRIAL	ERROR	DIRECTION	TIME (SEC	SUBJECT	TRIAL	ERROR	DIRECTION	TIME (SEC)
A	C1		1	1.4838	A	T1		1	2.38739
A	C1		2	1.3438	A	T1		2	1.85907
A	C1		3	0.9652	A	T1		3	1.58081
A	C1		4	1.7614	A	T1		4	2.3294
A	C1		5	1.3372	A	T1		5	2.48486
A	C1		6	1.365	A	T1		6	1.83013
A	C1	X	7	3.2283	A	T1		7	3.81594
A	C1		8	2.2329	A	T1	X	8	1.81142
A	C1		9	2.4517	A	T1		9	4.22065
A	C1		10	2.6947	A	T1		10	2.63851
A	C1		11	2.2267	A	T1		11	2.71675
A	C1		12	2.5162	A	T1		12	2.40385
A	C1		13	2.9332	A	T1	X	13	3.25345
A	C1		14	3.3143	A	T1		14	3.88906
A	C1		15	2.232	A	T1		15	5.08739
A	C1		16	2.4551	A	T1		16	1.89898
A	C1		17	2.4043	A	T1	X	17	8.73352
A	C1		18	3.4739	A	T1		18	3.29651
A	C1		19	3.297	A	T1	X	19	5.07101
A	C1		20	4.204	A	T1	X	20	2.78538
A	C1		21	4.5671	A	T1	X	21	3.82699
A	C1		22	4.7124	A	T1	X	22	8.65662
A	C1		23	3.5594	A	T1	X	23	5.47173
A	C1		24	3.2754	A	T1		24	7.73644
A	C1	X	25	10.3	A	T1	X	25	2.48069
A	C1		26	2.9337	A	T1	X	26	3.2516

SUBJECT	TRIAL	ERROR	DIRECTION	TIME (SEC)
A	C2		1	1.1976
A	C2		2	1.438
A	C2		3	0.9257
A	C2		4	0.9285
A	C2		5	1.722
A	C2		6	1.2346
A	C2		7	2.7778
A	C2		8	1.9851
A	C2		9	1.6238
A	C2		10	2.5886
A	C2		11	2.4409
A	C2		12	5.1864
A	C2		13	2.3915
A	C2		14	2.4897
A	C2		15	4.0632
A	C2		16	2.0781
A	C2		17	2.2602
A	C2		18	1.8905
A	C2		19	2.4444
A	C2		20	2.3149
A	C2		21	3.8824
A	C2		22	4.3198
A	C2		23	3.9038
A	C2		24	3.2613
A	C2	X	25	3.3771
A	C2		26	3.7057

SUBJECT	TRIAL	ERROR	DIRECTION	TIME (SEC)
A	T2		1	2.34416
A	T2		2	1.86363
A	T2		3	1.97759
A	T2		4	1.58047
A	T2		5	2.1062
A	T2		6	3.50786
A	T2	X	7	2.67871
A	T2	X	8	3.69784
A	T2		9	4.21606
A	T2		10	3.86133
A	T2		11	3.09941
A	T2		12	3.65954
A	T2		13	4.22111
A	T2		14	5.28203
A	T2	X	15	1.35596
A	T2		16	2.90439
A	T2		17	5.52342
A	T2		18	5.87872
A	T2	X	19	5.02667
A	T2		20	3.48165
A	T2	X	21	2.74703
A	T2	X	22	8.0175
A	T2		23	5.30824
A	T2		24	6.50398
A	T2	X	25	10.8893
A	T2	X	26	3.33599

SUBJECT	TRIAL	ERROR	DIRECTION	TIME (SEC)
B	T1		1	2.68024
B	T1		2	1.6909
B	T1		3	1.19751
B	T1		4	1.29108
B	T1		5	2.2127
B	T1		6	1.84077
B	T1		7	2.77905
B	T1		8	8.20622
B	T1		9	2.5886
B	T1		10	3.19228
B	T1		11	2.87355
B	T1	X	12	2.02877
B	T1	X	13	2.02118
B	T1		14	3.37081
B	T1		15	1.88189
B	T1		16	1.74958
B	T1		17	4.12923
B	T1		18	2.2561
B	T1		19	3.24795
B	T1	X	20	1.25721
B	T1	X	21	3.14024
B	T1	X	22	3.63554
B	T1	X	23	2.7592
B	T1	X	24	1.75009
B	T1	X	25	4.80546
B	T1		26	5.75393

SUBJECT	TRIAL	ERROR	DIRECTION	TIME (SEC)
B	C1		1	2.98032
B	C1		2	1.05012
B	C1		3	1.08743
B	C1		4	1.37954
B	C1		5	1.33872
B	C1		6	2.12102
B	C1	X	7	2.66705
B	C1		8	4.56844
B	C1		9	2.06568
B	C1		10	1.99279
B	C1		11	2.12334
B	C1		12	2.31164
B	C1		13	1.97039
B	C1		14	1.67943
B	C1		15	1.83158
B	C1		16	2.47035
B	C1		17	2.29623
B	C1		18	1.63876
B	C1		19	4.14479
B	C1		20	5.18628
B	C1		21	4.91524
B	C1		22	3.33851
B	C1		23	4.6692
B	C1		24	3.83097
B	C1		25	3.98602
B	C1		26	4.57183

SUBJECT	TRIAL	ERROR	DIRECTION	TIME (SEC)
B	C2		1	2.63206
B	C2		2	1.49282
B	C2		3	0.94863
B	C2		4	19.751
B	C2		5	1.2337
B	C2		6	1.73016
B	C2		7	2.01739
B	C2		8	2.88604
B	C2		9	2.1426
B	C2		10	1.98683
B	C2		11	1.53397
B	C2		12	2.86577
B	C2		13	1.63926
B	C2		14	2.12368
B	C2		15	1.3827
B	C2		16	2.55233
B	C2		17	2.35847
B	C2		18	2.27586
B	C2		19	3.41138
B	C2		20	3.03709
B	C2		21	4.52728
B	C2		22	3.84639
B	C2		23	3.10954
B	C2		24	3.78318
B	C2		25	4.2098
B	C2		26	3.57947

SUBJECT	TRIAL	ERROR	DIRECTION	TIME (SEC)
B	T2		1	2.31004
B	T2		2	1.81467
B	T2		3	1.27157
B	T2		4	1.49117
B	T2		5	1.70026
B	T2		6	2.37415
B	T2		7	2.73838
B	T2	X	8	1.52562
B	T2		9	2.7372
B	T2	X	10	2.14989
B	T2	X	11	1.90509
B	T2	X	12	3.12389
B	T2		13	2.60105
B	T2	X	14	2.00629
B	T2		15	1.69872
B	T2		16	1.39019
B	T2	X	17	3.70438
B	T2		18	4.64578
B	T2	X	19	1.72415
B	T2		20	4.16223
B	T2	X	21	2.33309
B	T2	X	22	1.65314
B	T2	X	23	2.32937
B	T2	X	24	1.84548
B	T2	X	25	3.01633
B	T2		26	7.579

SUBJECT	TRIAL	ERROR	DIRECTION	TIME (SEC)
C	T1		1	2.74281
C	T1		2	2.23234
C	T1		3	2.35136
C	T1		4	2.26804
C	T1		5	2.15352
C	T1		6	2.14942
C	T1	X	7	4.65712
C	T1		8	5.03619
C	T1		9	2.56682
C	T1		10	5.78886
C	T1		11	3.95094
C	T1		12	4.37121
C	T1		13	3.27679
C	T1		14	5.28108
C	T1	X	15	5.09115
C	T1	X	16	2.31178
C	T1	X	17	3.06192
C	T1		18	3.91765
C	T1	X	19	3.85926
C	T1	X	20	2.837
C	T1	X	21	5.16387
C	T1		22	5.54128
C	T1	X	23	2.72792
C	T1	X	24	2.33845
C	T1	X	25	4.13851
C	T1	X	26	2.62779

SUBJECT	TRIAL	ERROR	DIRECTION	TIME (SEC)
C	T2		1	2.61871
C	T2		2	1.86429
C	T2		3	1.636
C	T2		4	2.06755
C	T2		5	2.85666
C	T2		6	2.62337
C	T2		7	3.83017
C	T2		8	2.94617
C	T2		9	2.91932
C	T2	X	10	3.77143
C	T2		11	4.2544
C	T2		12	3.4
C	T2		13	1.91313
C	T2	X	14	5.49862
C	T2	X	15	1.76203
C	T2		16	3.37889
C	T2	X	17	1.84721
C	T2		18	4.14395
C	T2	X	19	5.55089
C	T2		20	3.93809
C	T2	X	21	5.26888
C	T2	X	22	3.87524
C	T2		23	3.98978
C	T2		24	2.37611
C	T2	X	25	1.98636
C	T2	X	26	5.67532

SUBJECT	TRIAL	ERROR	DIRECTION	TIME (SEC)
C	C1		1	1.33349
C	C1		2	1.21597
C	C1		3	1.54551
C	C1		4	1.81775
C	C1		5	1.3724
C	C1		6	1.7261
C	C1		7	3.02975
C	C1		8	2.74313
C	C1		9	1.61225
C	C1		10	2.08006
C	C1		11	2.14162
C	C1		12	3.65754
C	C1		13	2.05795
C	C1		14	1.87069
C	C1		15	1.37388
C	C1		16	3.05163
C	C1		17	2.75422
C	C1		18	4.02002
C	C1		19	1.99726
C	C1		20	2.38187
C	C1		21	4.41017
C	C1		22	3.11582
C	C1		23	2.73135
C	C1		24	4.28866
C	C1		25	1.76817
C	C1		26	3.39622

SUBJECT	TRIAL	ERROR	DIRECTION	TIME (SEC)
C	C2		1	1.62227
C	C2		2	1.69384
C	C2		3	1.3696
C	C2		4	2.09071
C	C2		5	1.94847
C	C2		6	1.70263
C	C2		7	14.2169
C	C2		8	2.60782
C	C2		9	1.94646
C	C2		10	2.78445
C	C2		11	3.57473
C	C2		12	4.03435
C	C2		13	2.49972
C	C2		14	2.0038
C	C2		15	2.99953
C	C2		16	2.23676
C	C2		17	2.6801
C	C2		18	2.04907
C	C2		19	3.58264
C	C2		20	2.33745
C	C2		21	2.86734
C	C2		22	3.86021
C	C2		23	3.83071
C	C2		24	2.24207
C	C2		25	4.07925
C	C2		26	3.08912

SUBJECT	TRIAL	ERROR	DIRECTION	TIME (SEC)
D	T1		1	4.98046
D	T1		2	3.56388
D	T1		3	2.47064
D	T1		4	3.26925
D	T1		5	3.13472
D	T1		6	3.12194
D	T1		7	5.39358
D	T1		8	9.66195
D	T1		9	5.10561
D	T1		10	8.98785
D	T1		11	10.0866
D	T1		12	6.96411
D	T1		13	5.06033
D	T1		14	7.47791
D	T1		15	5.40738
D	T1		16	7.8887
D	T1		17	5.80751
D	T1		18	4.53542
D	T1		19	7.80613
D	T1	X	20	6.44035
D	T1		21	11.1697
D	T1		22	5.60668
D	T1	X	23	5.84208
D	T1		24	8.18058
D	T1		25	12.382
D	T1	X	26	8.02816

SUBJECT	TRIAL	ERROR	DIRECTION	TIME (SEC)
D	C1		1	2.36037
D	C1		2	1.66741
D	C1		3	1.27232
D	C1		4	0.74523
D	C1		5	1.56871
D	C1		6	1.68067
D	C1		7	1.83216
D	C1		8	2.98427
D	C1		9	2.46768
D	C1		10	2.29195
D	C1		11	3.59664
D	C1		12	2.94813
D	C1		13	2.02218
D	C1		14	3.34141
D	C1		15	3.55856
D	C1		16	2.17843
D	C1		17	3.42311
D	C1		18	2.12478
D	C1		19	3.73747
D	C1		20	3.11252
D	C1		21	4.46659
D	C1		22	6.04427
D	C1		23	3.95848
D	C1		24	4.55457
D	C1		25	5.26415
D	C1		26	3.26588

SUBJECT	TRIAL	ERROR	DIRECTION	TIME (SEC)
D	C2		1	1.59129
D	C2		2	1.17003
D	C2		3	1.03168
D	C2		4	0.98149
D	C2		5	1.84151
D	C2		6	1.55181
D	C2		7	1.96195
D	C2		8	3.46396
D	C2		9	3.14896
D	C2		10	4.9165
D	C2		11	2.46287
D	C2		12	3.45882
D	C2	X	13	3.53462
D	C2		14	2.51929
D	C2		15	2.21945
D	C2		16	2.87991
D	C2		17	2.30582
D	C2		18	1.65858
D	C2		19	2.55721
D	C2		20	4.01781
D	C2		21	3.23911
D	C2		22	3.07004
D	C2		23	3.70604
D	C2	X	24	3.70295
D	C2		25	4.15238
D	C2		26	3.58003

SUBJECT	TRIAL	ERROR	DIRECTION	TIME (SEC)
D	T2		1	2.20075
D	T2		2	2.32102
D	T2		3	2.35098
D	T2		4	1.84165
D	T2		5	2.333
D	T2		6	2.7894
D	T2		7	7.24646
D	T2		8	3.06084
D	T2	X	9	1.52292
D	T2		10	2.36472
D	T2		11	6.43166
D	T2		12	4.22749
D	T2		13	2.73137
D	T2		14	7.55731
D	T2		15	2.05786
D	T2		16	2.31176
D	T2		17	3.72428
D	T2		18	4.09972
D	T2		19	6.76903
D	T2	X	20	3.80567
D	T2		21	7.6728
D	T2		22	7.20912
D	T2		23	4.78127
D	T2		24	3.91607
D	T2		25	6.69215
D	T2	X	26	3.85219

C2: ISS EVA DATA

SUBJECT	GENDER	DAY	PATH	SENSE	MODALITY	CODE	RT (ms)	MT (ms)	FAIL
1	1	1	0	0	0	0	60150	706169	0
1	1	1	1	1	1	2	41210		1
1	1	1	1	1	1	2	24880	211318	0
1	1	1	1	0	0	3	82825	341274	0
1	1	1	0	1	1	1	14360	371240	0
1	1	1	1	1	0	2	19640	249406	0
1	1	1	0	0	1	0	9980		1
1	1	1	0	0	1	0	11280	178978	0
1	1	1	0	1	0	1	11420	177638	0
1	1	1	1	0	1	3	19510	146424	0
1	1	2	1	0	0	3	4887	91100	0
1	1	2	0	1	1	1	3802	211550	0
1	1	2	0	0	0	0	13279	276810	0
1	1	2	1	1	1	2	2546	166510	0
1	1	2	0	1	0	1	10637		1
1	1	2	0	1	0	1	1578	219200	0
1	1	2	1	0	1	3	2647	84800	0
1	1	2	1	1	0	2	11983	181410	0
1	1	2	0	0	1	0	1460		0
2	1	1	1	0	0	3	47524		1
2	1	1	0	1	1	1	18261		1
2	1	1	0	0	0	0	8025		1
2	1	1	1	1	1	2	21137	570780	0
2	1	1	0	1	0	1	27961		1
2	1	1	1	0	1	3			1
2	1	1	1	1	0	2			1
2	1	1	0	0	1	0			1
2	1	2	0	0	0	0	16590	678371	0
2	1	2	1	1	1	2	14730	445782	0
2	1	2	1	0	0	3	18730		0
2	1	2	0	1	1	1	5500	389246	0
2	1	2	1	1	0	2	11190	781290	0
2	1	2	0	0	1	0	16590	524735	0
2	1	2	0	1	0	1	9090	601500	0
2	1	2	1	0	1	3	13880	374438	0
3	1	1	0	0	0	0	26490		1
3	1	1	1	1	1	2	10641		1
3	1	1	1	0	0	3	47243	530560	0
3	1	1	0	1	1	1	20729		1
3	1	1	1	1	0	2	12408		1
3	1	1	0	0	1	0	33929	268230	0
3	1	1	0	1	0	1	13232		1
3	1	1	1	0	1	3	16374		1
3	1	2	1	0	0	3	11570		1
3	1	2	0	1	1	1	16966		1

SUBJECT	GENDER	DAY	PATH	SENSE	MODALITY	CODE	RT (ms)	MT (ms)	FAIL
3	1	2	0	0	0	0	11928		1
3	1	2	1	1	1	2	9094	394470	0
3	1	2	0	1	0	1	12781		1
3	1	2	1	0	1	3	11396	181790	0
3	1	2	1	1	0	2	11672	229960	0
3	1	2	0	0	1	0	13962		1
4	1	1	1	0	0	3	34597		1
4	1	1	1	0	0	3	4019	470630	0
4	1	1	0	1	1	1	31847	218900	0
4	1	1	0	0	0	0	9631		1
4	1	1	0	0	0	0	3888	577220	0
4	1	1	1	1	1	2	9625		1
4	1	1	0	1	0	1	17245	424718	0
4	1	1	1	0	1	3	14777	214629	0
4	1	1	1	1	0	2	16340	167156	0
4	1	1	0	0	1	0	17360	286626	0
4	1	2	0	0	0	0	10505	521080	0
4	1	2	1	1	1	2	12087	211860	0
4	1	2	1	0	0	3	23346	179450	0
4	1	2	0	1	1	1	15335	104860	0
4	1	2	1	1	0	2	17707	200300	0
4	1	2	0	0	1	0	13296		1
4	1	2	0	0	1	0	10603	385020	0
4	1	2	0	1	0	1	4190	407650	0
4	1	2	1	0	1	3	10320	156650	0
5	1	1	0	0	0	0	16321	305340	0
5	1	1	1	1	1	2	22550		1
5	1	1	1	0	0	3	26596		1
5	1	1	0	1	1	1	34563	430590	0
5	1	1	1	1	0	2	14887	553910	0
5	1	1	0	0	1	0	2260	314000	0
5	1	1	0	1	0	1	23509		1
5	1	1	1	0	1	3			1
5	1	2	1	0	0	3	39710	267760	0
5	1	2	0	1	1	1	15715	141130	0
5	1	2	0	0	0	0	6682	256380	0
5	1	2	1	1	1	2	6293	105950	0
5	1	2	0	1	0	1	12972	208100	0
5	1	2	1	0	1	3	6145		1
5	1	2	1	1	0	2	9250	301850	0
5	1	2	0	0	1	0	7773		1
6	1	1	1	0	0	3	18536	224876	0
6	1	1	0	1	1	1	14611	181980	0
6	1	1	0	0	0	0	18994	187500	0
6	1	1	1	1	1	2	11911	263060	0
6	1	1	0	1	0	1	12297	165440	0

SUBJECT	GENDER	DAY	PATH	SENSE	MODALITY	CODE	RT (ms)	MT (ms)	FAIL
6	1	1	1	0	1	3	15052	202910	0
6	1	1	1	1	0	2	12661	318440	0
6	1	1	0	0	1	0	8074	120890	0
6	1	2	0	0	0	0	14016	140990	0
6	1	2	1	1	1	2	11664	299690	0
6	1	2	1	0	0	3	9666	113830	0
6	1	2	0	1	1	1	5663		1
6	1	2	0	1	1	1	4014	220600	0
6	1	2	1	1	0	2	6928	376630	0
6	1	2	0	0	1	0	7928		1
6	1	2	0	0	1	0	11345	266130	0
6	1	2	0	1	0	1	6005	294090	0
6	1	2	1	0	1	3	9531	158710	0
7	0	1	0	0	0	0	25622	491160	0
7	0	1	1	1	1	2	25135		1
7	0	1	1	1	1	2	24125	321240	0
7	0	1	1	0	0	3	17000	394490	0
7	0	1	0	1	1	1	6319	435270	0
7	0	1	1	1	0	2	15694		1
7	0	1	0	0	1	0	11015		1
7	0	1	0	1	0	1	6375		1
7	0	1	1	0	1	3	6440		1
7	0	2	1	0	0	3	10156	425910	0
7	0	2	0	1	1	1	4466	555040	0
7	0	2	0	0	0	0	5905		1
7	0	2	0	0	0	0	7254		1
7	0	2	1	1	1	2	3006	228480	0
7	0	2	0	1	0	1	5278		1
7	0	2	1	0	1	3	6944	374050	0
7	0	2	1	1	0	2	20723	674050	0
7	0	2	0	0	1	0	8116		1
8	0	1	1	0	0	3	37614	274120	0
8	0	1	0	1	1	1	8387		1
8	0	1	0	1	1	1	1629	228660	0
8	0	1	0	0	0	0	10769	248410	0
8	0	1	1	1	1	2	10413	283310	0
8	0	1	0	1	0	1	17999	244100	0
8	0	1	1	0	1	3	19724	230320	0
8	0	1	1	1	0	2	6080		1
8	0	1	1	1	0	2	7028		1
8	0	1	0	0	1	0	26792	317570	0
8	0	2	0	0	0	0	9918	263760	0
8	0	2	1	1	1	2	9429	340610	0
8	0	2	1	0	0	3	16000	291200	0
8	0	2	0	1	1	1	9189	167700	0
8	0	2	1	1	0	2	5602	223810	0

SUBJECT	GENDER	DAY	PATH	SENSE	MODALITY	CODE	RT (ms)	MT (ms)	FAIL
8	0	2	0	0	1	0	7541	198500	0
8	0	2	0	1	0	1	7736	171060	0
8	0	2	1	0	1	3	2223	137170	0
9	0	1	0	0	0	0	20658	481340	0
9	0	1	1	1	1	2	24927	218900	0
9	0	1	1	0	0	3	15159	113380	0
9	0	1	0	1	1	1	3641		1
9	0	1	0	1	1	1	4522	432710	0
9	0	1	1	1	0	2	20002		1
9	0	1	1	1	0	2	5074	358910	0
9	0	1	0	0	1	0	4978	103110	0
9	0	1	0	1	0	1	14945	342840	0
9	0	1	1	0	1	3	9324	173050	0
9	0	2	1	0	0	3	11623	150490	0
9	0	2	0	1	1	1	9000	595450	0
9	0	2	0	0	0	0	13525	168540	0
9	0	2	1	1	1	2	5332	256460	0
9	0	2	0	1	0	1	4240		1
9	0	2	0	1	0	1	3531	207950	0
9	0	2	1	0	1	3	2665	125210	0
9	0	2	1	1	0	2	6570	359050	0
9	0	2	0	0	1	0	7732	182050	0
10	0	1	1	0	0	3	32029		1
10	0	1	1	0	0	3	16432	724770	0
10	0	1	0	1	1	1	12192		1
10	0	1	0	0	0	0	23295	792850	0
10	0	1	1	1	1	2	27475		1
10	0	1	0	1	0	1	8938		1
10	0	1	0	1	0	1	2362	584010	0
10	0	1	1	0	1	3	8990	273800	0
10	0	1	1	1	0	2	23036	730000	0
10	0	1	0	0	1	0	15491	303090	0
10	0	2	0	0	0	0	9405		1
10	0	2	0	0	0	0	10410	638880	0
10	0	2	1	1	1	2	18525	550160	0
10	0	2	1	0	0	3	39408	568990	0
10	0	2	0	1	1	1	32936	491090	0
10	0	2	1	1	0	2	20318	515360	0
10	0	2	0	0	1	0	22050		1
10	0	2	0	0	1	0	7726	474950	0
10	0	2	0	1	0	1	4185	403290	0
10	0	2	1	0	1	3	10145	412595	0
11	0	1	0	0	0	0	18047		1
11	0	1	1	1	1	2	3719		1
11	0	1	1	0	0	3	19643		1
11	0	1	0	1	1	1	10474	106950	0

SUBJECT	GENDER	DAY	PATH	SENSE	MODALITY	CODE	RT (ms)	MT (ms)	FAIL
11	0	1	1	1	0	2	14035		1
11	0	1	0	0	1	0	12287	166080	0
11	0	1	0	1	0	1	2012		1
11	0	1	1	0	1	3	5091	175460	0
11	0	2	1	0	0	3	17490		1
11	0	2	0	1	1	1	7280	170010	0
11	0	2	0	0	0	0	6907	146290	0
11	0	2	1	1	1	2	2332	194830	0
11	0	2	0	1	0	1	2909		1
11	0	2	1	0	1	3	4013		1
11	0	2	1	1	0	2	9389		1
11	0	2	0	0	1	0	2207		1
12	0	1	1	0	0	3	32525	327680	0
12	0	1	0	1	1	1	1670		1
12	0	1	0	0	0	0	14278		1
12	0	1	0	0	0	0	6967	407720	0
12	0	1	1	1	1	2	12130	185220	0
12	0	1	0	1	0	1	8090	255560	0
12	0	1	1	0	1	3	11004	209130	0
12	0	1	1	1	0	2	12082		1
12	0	1	1	1	0	2	10584		1
12	0	1	0	0	1	0	5900	174660	0
12	0	2	0	0	0	0	13060		1
12	0	2	1	1	1	2	9028	211310	0
12	0	2	1	0	0	3	9249		1
12	0	2	0	1	1	1	11915	280950	0
12	0	2	1	1	0	2	10763	517930	0
12	0	2	0	0	1	0	11313	495790	0
12	0	2	0	1	0	1	27815	275620	0
12	0	2	1	0	1	3	10503	504830	0

RT (sec)								
CONDITION	X1	X2	X3	X4	X5	X6	X7	X8
P-S-D CODE	X0000	X0001	X0010	X0011	X0100	X0101	X0110	X0111
SUBJECT								
1	60.15	13.279	11.42	10.637	82.825	4.887	19.64	11.983
2	8.025	16.59	27.961	9.09	47.524	18.73		11.19
3	26.49	11.928	13.232	12.781	47.243	11.57	12.408	11.672
4	9.631	10.505	17.245	4.19	34.597	23.346	16.34	17.707
5	16.321	6.682	23.059	12.972	26.596	39.71	14.887	9.25
6	18.994	14.016	12.297	6.005	18.536	9.666	12.661	6.928
7	25.622	5.905	6.375	5.278	17	10.156	15.964	20.723
8	10.769	9.918	17.999	7.736	37.614	16	6.08	5.602
9	20.658	13.525	14.945	4.24	15.159	11.623	20.002	6.57
10	23.295	9.405	8.938	4.185	32.029	39.408	23.036	20.318
11	18.047	6.907	2.012	2.909	19.643	17.49	14.035	9.389
12	14.278	13.06	8.09	27.815	32.525	9.249	12.082	10.763
CONDITION	X8	X9	X10	X11	X12	X13	X14	X15
P-S-D CODE	X1000	X1001	X1010	X1011	X1100	X1101	X1110	X1111
SUBJECT								
1	9.98	1.46	14.36	3.802	19.51	2.647	24.88	2.546
2		16.59	18.261	5.5		13.88	21.137	14.73
3	33.929	13.962	20.729	16.966	16.374	11.396	10.641	9.094
4	17.36	13.296	31.847	15.335	14.777	10.32	9.625	12.087
5	2.26	7.773	34.563	15.715		6.145	22.55	6.293
6	8.074	7.928	14.611	5.663	15.052	9.531	11.911	11.664
7	11.015	8.116	6.319	4.466	6.44	6.944	25.135	3.006
8	26.792	7.541	8.387	9.189	19.724	2.223	10.413	9.429
9	4.978	7.732	3.641	9	9.324	2.665	24.927	5.332
10	15.491	22.05	12.192	32.936	8.99	10.145	27.475	18.525
11	12.287	2.201	10.474	7.28	5.091	4.013	3.719	2.332
12	5.9	11.313	1.67	11.915	11.004	10.503	12.13	9.028
EFFECTS(sec)	X1-X9	X2-X10	X3-X11	X4-X12	X5-X13	X6-X14	X7-X15	X8-X16
SUBJECT								
1	50.17	11.819	-2.94	6.835	63.315	2.24	-5.24	9.437
2		0	9.7	3.59		4.85		-3.54
3	-7.439	-2.034	-7.497	-4.185	30.869	0.174	1.767	2.578
4	-7.729	-2.791	-14.6	-11.15	19.82	13.026	6.715	5.62
5	14.061	-1.091	-11.5	-2.743		33.565	-7.663	2.957
6	10.92	6.088	-2.314	0.342	3.484	0.135	0.75	-4.736
7	14.607	-2.211	0.056	0.812	10.56	3.212	-9.171	17.717
8	-16.02	2.377	9.612	-1.453	17.89	13.777	-4.333	-3.827
9	15.68	5.793	11.304	-4.76	5.835	8.958	-4.925	1.238
10	7.804	-12.65	-3.254	-28.75	23.039	29.263	-4.439	1.793
11	5.76	4.706	-8.462	-4.371	14.552	13.477	10.316	7.057
12	8.378	1.747	6.42	15.9	21.521	-1.254	-0.048	1.735

MT (sec)								
CONDITION	X1	X2	X3	X4	X5	X6	X7	X8
P-S-D CODE	X0000	X0001	X0010	X0011	X0100	X0101	X0110	X0111
SUBJECT								
1	706.17	276.81	177.638	219.2	341.27	91.1	249.41	181.41
2		678.37		601.5				781.29
3					530.56	268.23		229.96
4	577.22	521.08	424.718	407.65	470.63	176.45	167.16	200.3
5	305.34	256.38	.	208.1	.	267.76	553.91	301.85
6	187.5	140.99	165.44	294.09	224.88	113.83	318.44	376.63
7	491.16				394.49	425.91		674.05
8	248.41	263.76	244.1	171.06	274.12	291.2		223.81
9	481.34	168.54	342.84	207.95	113.38	150.49	358.91	359.05
10	792.85	638.88	584.01	403.29	724.77	568.99	730	515.36
11		146.29						
12	407.72		255.56	275.62	327.68			517.93
CONDITION	X8	X9	X10	X11	X12	X13	X14	X15
P-S-D CODE	X1000	X1001	X1010	X1011	X1100	X1101	X1110	X1111
SUBJECT								
1	178.98		371.24	211.55	146.42	84.8	211.32	166.51
2		524.74		389.25		374.44	570.78	445.78
3		394.47		181.79				214.63
4	286.63	385.02	218.9	104.86	214.63	156.65		211.86
5	314		430.59	141.13				105.95
6	120.89	266.13	181.98	220.6	202.91	158.71	263.06	299.69
7			435.27	555.04		374.05	321.24	228.48
8	317.57	198.5	228.66	167.7	230.32	137.17	283.31	340.61
9	103.11	182.05	432.71	595.45	173.05	125.21	218.9	256.46
10	303.09	474.95		491.09	273.8	412.6		550.16
11	166.08		106.95	170.01	175.46			194.83
12	174.66	495.79		280.95	209.13	504.83	185.22	211.31
EFFECTS(sec)	X1-X9	X2-X10	X3-X11	X4-X12	X5-X13	X6-X14	X7-X15	X8-X16
SUBJECT	527.19		-193.6	7.65	194.85	6.3	38.088	14.9
1		153.64		212.25				335.51
2								15.331
3	290.59	136.06	205.818	302.79	256	19.8		-11.56
4	-8.66			66.97				195.9
5	66.61	-125.1	-16.54	73.49	21.966	-44.88	55.38	76.94
6						51.86		445.57
7	-69.16	65.26	15.44	3.36	43.8	154.03		-116.8
8	378.23	-13.51	-89.87	-387.5	-59.67	25.28	140.01	102.59
9	489.76	163.93		-87.8	450.97	156.4		-34.8
10								.
11	233.06			-5.33	118.55			306.62
12								

APPENDIX D: NAVIGATION RECOMMENDATIONS FOR HELICOPTER HOVER

A helicopter in a hovering mode will use the INS navigation solution, with GPS aiding for bounding error growth (among other advantages previously discussed). The primary obstacle to overcome in this application is the packaging of the unit into a comfortable and unobtrusive configuration. In weightlessness, size, weight and volume are perhaps of lower priority, however in this application where the unit is in direct contact with the pilot, it is of extreme importance. GPS technology is quite compact relative to INS hardware, although great effort is being made to miniaturize many of the INS electronics. It is important to note that the latest miniature INS hardware is accurate only for short term (under ten minutes) term. Another requirement which places the lower limit on size and volume, is the desire to make modifications to the package if necessary; preventing the use of a completely miniaturized unit.

Perhaps the most difficult aspect of the helicopter application is the initial alignment of the INS gyros. The two components to this process are leveling and North seeking. Leveling establishes one plane of the platform perpendicular to the local gravity vector by nulling accelerometer output placed orthogonal to one another. Leveling of a strap-down system has the advantage that it can be accomplished mathematically. North seeking defines a reference direction in the leveled plane of the accelerometers through gyrocompassing. Leveling and gyrocompassing can be accomplished on the ground before flight, or in-flight with GPS aiding. To level the INS in-flight, the GPS will provide precise velocity information to compare with the INS velocity information, and the alignment parameters will be adjusted to drive the residuals to zero [Greenspan, 1996].

When the pilot is flying straight and level, the TLS will produce no stimulation. Only when the pilot deviates from this course will he/she sense any vibrotactile stimulation (unless the suit is configured at the time for target recognition). It has been assumed that "straight" will not always apply to due North, and therefore the process of establishing a reference direction should be flexible and alterable. An example of this is a pilot flying between to radio beacons, following a set course. The reference direction in this case will be the heading of the radio beacon towards which the pilot is flying. Therefore, it should be possible for the pilot to dial-in, or zero, the INS to the desired heading during flight. Of course, if the heading is known prior to takeoff, the alignment may be carried out on the ground by pointing the plane in the direction of that heading. Another option is to align the INS while the aircraft is pointing along a runway of known heading. One concern is that while a pilot sitting still will most likely provide a stable enough position for INS alignment, misalignments may be reduced by allowing the unit to rest fixed in the vehicle to self-align while the pilot performs any necessary pre-flight procedures. Once the alignment is complete, the pilot may then place the unit on her body, making sure that he feels the tactile stimulation that will arise from the motion of bringing the unit to their body from its initial position. When in place, the pilot may zero the unit to the desired heading.

Finally, the GPS antenna must be placed rigidly on the vehicle frame (as opposed to the body) for precise position determination, however, the antenna is not likely to be placed at the pilot's zenith due to interfering helicopter structures. If the antenna is placed some distance away from the pilot, the GPS will measure its position, while the INS will measure the pilot's position allowing the difference to be accounted for in the navigation solution.

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