Visual Interface Issues in a Virtual Environment for Space Teleoperation

by

Mark Edward Vidov

Submitted to the Department of Aeronautics and Astronautics
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Abstract

This thesis presents an investigation into the effect of the visual interface in a virtual environment teleoperation tracking task on operator performance and strategy. The design and implementation of a virtual environment teleoperation simulator for experimentation with human operators in a laboratory setting are described. Included are the considerations and specific details of the computer simulation model of the dynamics of a teleoperated remote vehicle and of the remote environment and the objects within it. The system description includes the control station, which allows the operator to manually control the motion of the vehicle, and the visual display to provide a real-time view of the simulated environment. The primary issues under investigation are presented, including the choice of display configuration, between video monitor display and a head mounted stereoscopic display, the addition of head tracking to provide operator control over the perspective view of the environment, and finally the addition of a visual cue fixed with respect to the remote vehicle body and its effect in reducing operator disorientation. The task implemented for experimentation is described, namely a moving target tracking task with obstacle avoidance in a planar virtual environment. Results are presented from experiments with human subjects in order to test the hypothesis that significant differences in human operator performance and control strategy may be attributed to the variables of display configuration. Conclusions are presented on the basis of these results and a discussion and evaluation of the virtual environment teleoperator are included.

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Thank God.

Of course there are others.

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The best for last: Mom and Dad and Jeff and Cat, my ever-concerned but supportive family. Patricia, dontcha know me? Maybe we will spend some time together soon.

And of course life is meaningless without my teams: Jays (World Series eh?) and Leafs (someday) and all the other lovable losers.

Times, they are a changin' — Bob Dylan

Times are changin' back — Bob Roberts

Those who wish to be
Must put aside the alienation
Get on with the fascination
The real relation
The underlying theme — Neil Peart

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Chapter 1

Introduction

This research is an investigation into the effect of the visual interface in a virtual environment teleoperation tracking task on operator performance and strategy. A virtual environment teleoperation simulator for experimentation with human operators in a laboratory setting has been designed and implemented. The system is based upon a computer model of the dynamics of a teleoperated remote vehicle and of the remote environment and the objects within it. The primary system components are the control station, where the operator manually control the motion of the vehicle, and the visual display which provides a real-time view of the simulated environment. There are three primary issues under investigation, including the choice of display configuration, between video monitor display and a head mounted stereoscopic display, the addition of head tracking to provide operator control over the perspective view of the environment, and finally the addition of a visual cue fixed with respect to the remote vehicle body and its effect in reducing operator disorientation. A moving target tracking task with obstacle avoidance in a planar virtual environment has been implemented for experimentation.

1.1 Motivation and Background

Virtual reality has received much sensationalist popular attention. However, when discussed without reference to an actual system, the attention is mostly unproductive.

More interesting is an examination of the technologies involved and the numerous developing and potential applications. A number of virtual environment systems currently exist for practical applications, such as the exploration of terrain data (NASA Ames[21]) and to simulate molecular docking and manipulation (UNC Chapel Hill). The primary motivation of this research is to build and test a virtual environment teleoperation simulator (VETS). A virtual environment (VE) is, in practical terms, a computer model of an environment and the objects within it, presented to a human who has some means of interacting with the environment. The concept is quite simple: the virtual environment does not actually exist but physical devices provide a window through which a person can observe and manipulate objects within the environment. This section describes how the virtual environment concept is applied and reasons for use.

A computer model is the ideal framework for a virtual environment. There are no strict requirements for what should be included in the model, but whatever is included is strictly enforced. The model takes a mathematical (dynamic) description and applies it in real-time, continually computing and updating the state of the environment. It differs from many computer models in that a human provides an input over the complete period of operation (as opposed to the start of operation). There are many physical devices which allow a human to manipulate and observe the model. The interaction of the human and the computer model establishes the virtual environment. The computer model in operation is termed a simulation.

The human in the loop receives information from the simulation typically through visual displays, such as computer monitors or head mounted displays. The simulation receives command inputs through a number of devices, including keyboards, joysticks, trackballs, and data-gloves. The type of view presented and the control allowed are major design considerations. The term telepresence refers to the sensation of actually being within the environment as opposed to simply viewing it. A stereoscopic display enhances telepresence by creating the illusion of depth and three-dimensionality. Input devices which conform to the mental models of the operators also enhance telepresence. For instance, pushing a joystick forward should cause a forward motion, and so on. The most typical virtual environment is a three-dimensional world with objects. The operator has the ability to navigate within the environment and interact with the objects. The computer model defines the structure and behaviour of all components of the virtual environment.

A flight simulator is the closest relative to a virtual environment. The most advanced simulators try to physically model an airplane cockpit exactly. The pilot is presented a simulated canopy view out of the cockpit, possibly with the addition of a head-up display. The pilot can also engage in all standard activities, from takeoff to freeflight to landing. The simulation recognizes control signals and modifies the display accordingly. The simulator behaves like a real airplane because the complex dynamics and control of an airplane are included in the computer model.

1.2 Research Objectives

This thesis discusses the development and issues related to a virtual environment for space teleoperation. Teleoperation refers to human control of a remote vehicle or robot. Control primarily means control of motion, although activities such as telemanipulation of robotic arms are possible. Space teleoperation is a demanding task. Cameras are typically mounted on the remote vehicle and may also be placed throughout the remote environment to provide a view of the operation. The operator can then perform tasks in the remote environment by commanding the motion and activities of the robot. What makes teleoperation particularly adaptable to a VE simulation is that the operator does not need to leave the control station. In fact, space teleoperation may not even require people in space (unless time lag is a significant factor). A VE simulation does not even require a robot. While the control station is identical, the commands in a VE simulator are fed to a program in which the robot is modelled. The program output is an updated view of the artificial environment, presented to the operator at the control station. VETS provides infinite flexibility in the choice of robot and environment.

It is very difficult to examine the behaviour of a free flying unmanned remote vehicle or robot without actually building a robot for space. Free flying involves motion in up to six degrees of freedom (equal to three translational plus three rotational). VETS can simply and completely model these dynamics. In fact, the mathematical model of the dynamics is easily modified for numerous operating conditions. Some of the major issues in teleoperation relate to the human operator in control of the vehicle. Teleoperation requires continuous interaction between operator and vehicle. The control station, the site of the interaction, serves two purposes: to provide information from or about the vehicle to the operator and to transmit commands from the operator to the vehicle.

While the information provided to the teleoperator (in both teleoperation and virtual environement teleoperation) may have many forms (visual, auditory, tactual, numeric), this study examines only visual feedback of the environment in real-time (i.e. without delay or processing). Specifically, feedback is provided by a camera mounted on the front of the remote vehicle. The image is presented to the operator at the control station on a monitor. The form of the image and the method of display give rise to the first few issues of this study. The first issue is the type of monitor display used to present the environment. The standard technique is to use a single fixed camera on the vehicle, with the image presented on a single monitor display (color or monochrome). In VETS, the technique is similar: the viewpoint of the animation (simulation) is a single point fixed relative to the simulated vehicle. One altenative to this arrangement, which is being investigated, is the use of a steroscopic display. In teleoperation, a pair of properly aligned cameras are mounted on the vehicle and the dual images presented to the operator on a stereoscopic display. The most fashionable display for such a task is the head mounted display. This device, worn directly on the head, presents the images from the left and right cameras directly to the left and right eyes (via optics or liquid crystal displays). The first hypothesis to be tested is whether the head mounted stereoscopic display enhances the human operator's perception of the remote environement and allows for performance gains in teleoperation tasks.

An additional consideration arises with regard to the stereoscopic display. It is possible to give the operator control over the direction of view of the camera pair mounted on the vehicle by tracking the orientation of the operator's head. For instance, if the operator wishes to rotate the cameras clockwise, they simply turn their head clockwise and the cameras follow. Head tracking is expected to provide additional information about the remote environement. This thesis examines whether this is the case or whether head tracking actually increases disorientation and degrades operator performance.

To examine operator disorientation and control accuracy in teleoperation tasks, the addition of a fixed visual reference to the environment is implemented. Disorientation has been know to occur to fighter pilots while looking out the clear bubble canopy. Without a fixed visible reference to their own vehicle, pilots easily loose track of their orientation and heading relative to the world, as well as their own orientation relative to the plane. Such disorientation is common in teleoperation and usually arises in the form of the questions "which way am I [the vehicle and its camera] facing?" and "which way is up?". A vehicle body reference, similar to a car window frame, can be added to the image. Thus, no matter how the camera is oriented, the reference frame, fixed with respect to the vehicle, indicates how the vehicle is oriented. The hypothesis is that this visual cue reduces disorientation and increases accuracy in teleoperation, particularly when used with head tracking.

While these issues specifically relate to teleoperation, a virtual environment teleoperation simulator provides an ideal framework for their investigation. The previous paragraphs discussed teleoperator performance. In VETS, performance can be measured by designing structured teleoperation tasks. The flexibility of the virtual environment allows for rapid design and implementation of tasks. Actual teleoperation has numerous and time consuming operational considerations which take priority before experimentation. A computer simulation actually provides a number of advantages over true teleoperation. The first is the ability to modify the workspace and environment. The second is the ability to modify vehicle dynamics. While time response in true teleoperation depends on many factors throughout the system, it can be more carefully controlled in a simulation. Success of a simulation depends on these factors as well as others which describe the quality of the simulation. The main limitation in simulation is the graphical processing capabilities of the system. To provide smooth animation, the frame rate (the rate at which successive images are computed and rendered) must be high enough. In practice, this depends heavily on the complexity of the image displayed. Simulation allows the use of graphical techniques from shadowing to antialiasing to improve image quality. Certain attributes are much easier to include in a virtual environment. For instance, the body representation of the vehicle is a simple overlaying graphical object in a virtual environment but requires specialized hardware to implement in teleoperation.

In summary, the design requirement of this investigation is to implement a virtual environment teleoperation simulator consisting of the control station with display and input devices and the computer system which performs dynamic and graphical computations required to create and display the virtual environment. The research objectives are to investigate human operator performance and control strategy in a teleoperation task and to specifically determine the effects of three primary display factors: monitor type, use of head tracking and the addition of a body representation.

Before getting into more detail about the teleoperation simulator, the reader may be interested in related teleoperation work within the Laboratory For Space Teleoperation and Robotics (LSTAR)[4, 23]. The lab has designed and built STAR, an underwater free-flying teleoperated robot to simulate a free-flying space robot. STAR is a platform for the implementation and testing of a number of control and robotics techniques, including vision-based navigation and telemanipulation. A number of components of STAR's control station were found to be perfectly adaptable to VETS' control station requirements. The ultimate goal of this research is to apply this knowledge to actual teleoperation systems such as STAR. The fact that there are a number of physical and operational similarities between the platforms enhances the ability to port this knowledge and experience.

1.3 Thesis Outline

Chapter 2 describes the design criteria and the actual implementation of a virtual environment teleoperation simulator. Chapter 3 discusses the experimental objectives and requirements and the specifics of the experimental procedure. Chapter 4 presents the form and details of the data derived from experiments with human subjects. A number of alternatives for data processing and analysis are presented. Chapter 5 analyzes the results in detail, using a number of numerical and statistical techniques. Chapter 6 summarizes and discusses the results, and also considers some of the system and experimental limitations as well as recommendations for future studies.

Chapter 2

Virtual Environment Teleoperation Simulator (VETS)

The virtual environment teleoperation simulator provides a platform for the investigation of visual interface issues in teleoperation. One of the primary design goals is the ability to make use of various hardware components, such as display, computer and interface components. The software system is also modular, allowing simple and rapid modification and enhancement at any stage of development. This chapter describes the origin and application of these goals and the resulting implementation of the teleoperation simulator.

2.1 Design and Organization

The previous chapter introduced the concept of a virtual environment teleoperation simulator. This chapter discusses its implementation and the various requirements leading to specific choices of components and structure. VETS specifically consists of two primary components. The first is the control station, where the operator is able to view the vehicle's environment and to send commands to the vehicle. The second component is the computer system which receives operator commands, computes vehicle dynamics and creates an updated image of the environment, sending it back to the control station. This short description highlights all of the main components and interactions of the system. This section lists the issues and alternatives of the system while the following describe each component in greater detail.

The control station can be interpreted as the interface between human and machine. All that the operator knows about the vehicle's situation is taken from information at the control station. Similarly, the vehicle's behaviour can be modified only by operator commands through the control station. The control station includes at least two components: a display device to present the image of the environment and an input device for operator commands to the vehicle. As discussed in Chapter 1, the two choices for display device include a monitor and a head mounted stereoscopic display. The input devices depend specifically on what type of control is desired. Joysticks are used primarily to convey directional movement commands to the vehicle. A head tracking device conveys camera orientation commands.

The choice of vehicle dynamics is one of the more significant and detailed design considerations. The dynamics describe the complete behaviour of the remote vehicle in its environment. To simulate space teleoperation, six degree of freedom (dof) inertial dynamics are required, with three dof each for translation and rotation. Vehicle motion is controlled by directional thruster commands by the operator. Any subset of these degrees of freedom can be implemented and the type of control is also a variable.

Graphical transformations convert the position of objects within the environment, resulting from dynamics computations, into a perspective view and into an image to be displayed on a monitor. A computer system with graphical processing capabilities is specially adapted to such rapid computations.

The following sections discuss the design choices in detail. As a whole, the typical operation of VETS can be imagined as follows: a human operator seated at the control station is able to view a display device to observe the status of a remote vehicle. Devices allow the operator to send commands to the vehicle over the complete period of operation. The remote vehicle maneuvers and performs tasks within its environment in response to operator commands. The specifics of the operations and tasks will be left for the following chapter.

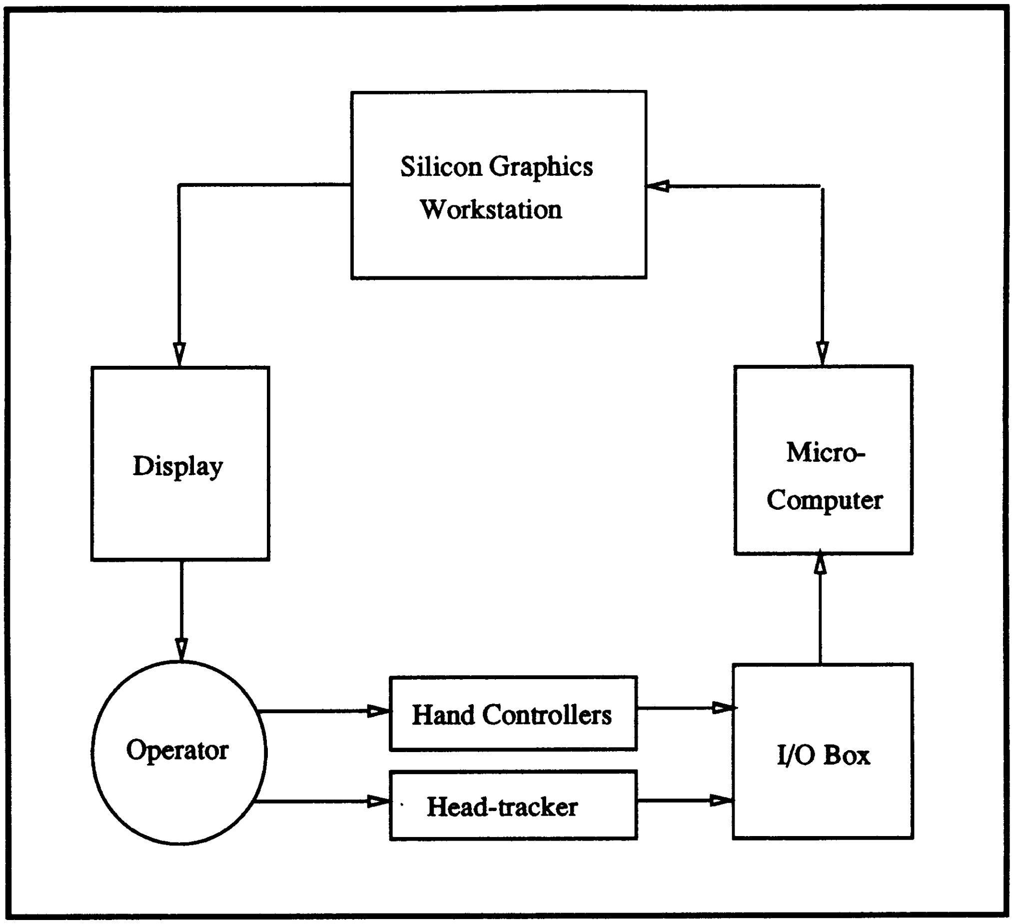

Figure 2-1: **Teleoperation Simulator**

2.2 Simulator Design

The teleoperation simulator consists of the control station, the computational engine and the devices which link the two stages. The block diagram of Figure 2-1 is the complete system. The human operator is an important component in the loop. The control station is the human interface which allows the operator to input commands to the remote vehicle. A pair of three dof hand controllers or joysticks are used to command vehicle motion and six dof mechanical linkage head tracker commands the stereoscopic camera pair. This setup is used in both the teleoperation of STAR and the teleoperation simulator.

The joysticks are mounted and configured such that the left hand stick provides translational control (X-Y-Z) and the right stick provides rotational control (Yaw-

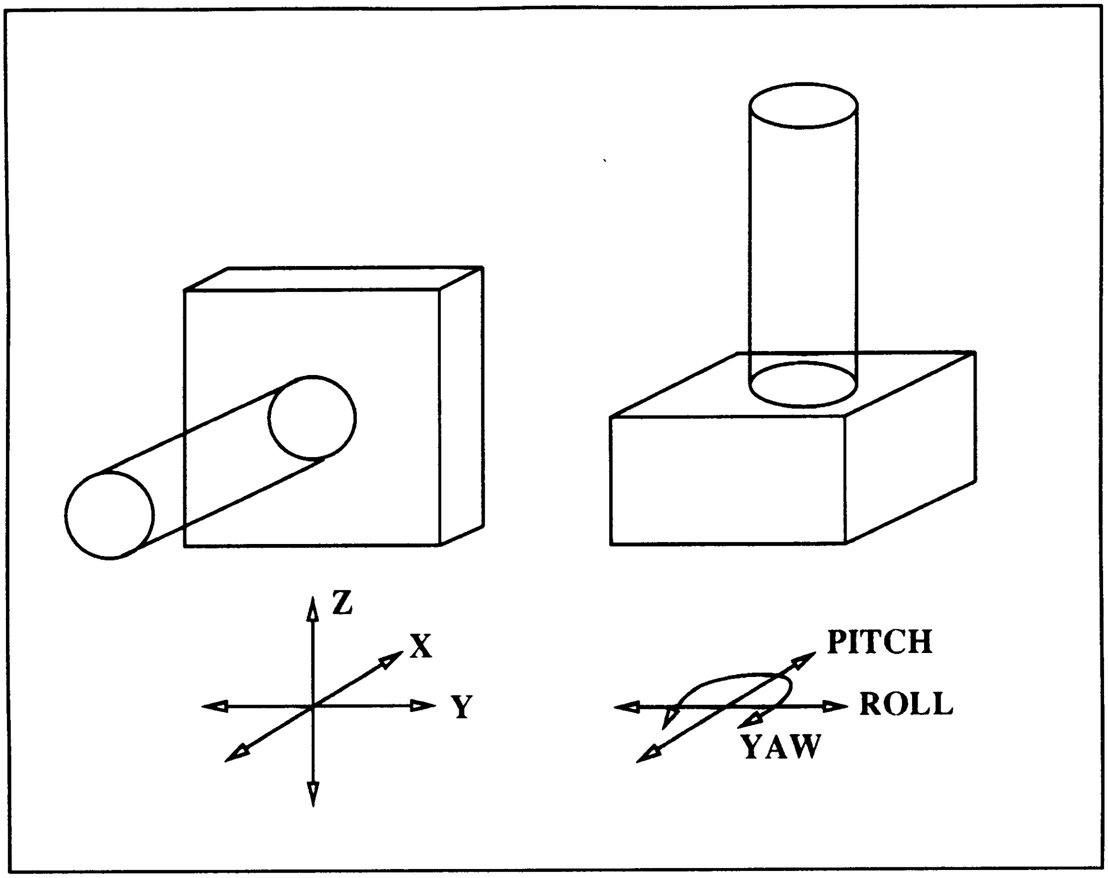

Figure 2-2: **Joystick Configuration**

Pitch-Roll) (Figure 2-2). The joysticks are three dof displacement-type, proportional hand controllers from P-Q Controls (Models 220-19, 220-21) The order of the control (i.e. the type of response to a joystick defection) is a variable which may be programmed in the software which commands the vehicle's thrusters.

The head tracker is a mechanical linkage system providing six dof; three rotation and three translation (Figure 2-3). It consists of two links joined at an axis of rotation, with the end of one link joined to a fixed base and the end of the other joined to a head mounted display. A total of six rotation axis are provided by potentiometers at the joints. The combination of one roll, two yaw and three pitch axes provides full freedom of motion. Although operators are seated, they have a range of motion approximately within a radius of one meter from nominal. The end taps of the pots are connected to positive and negative voltages. Joint angles are obtained by shaft

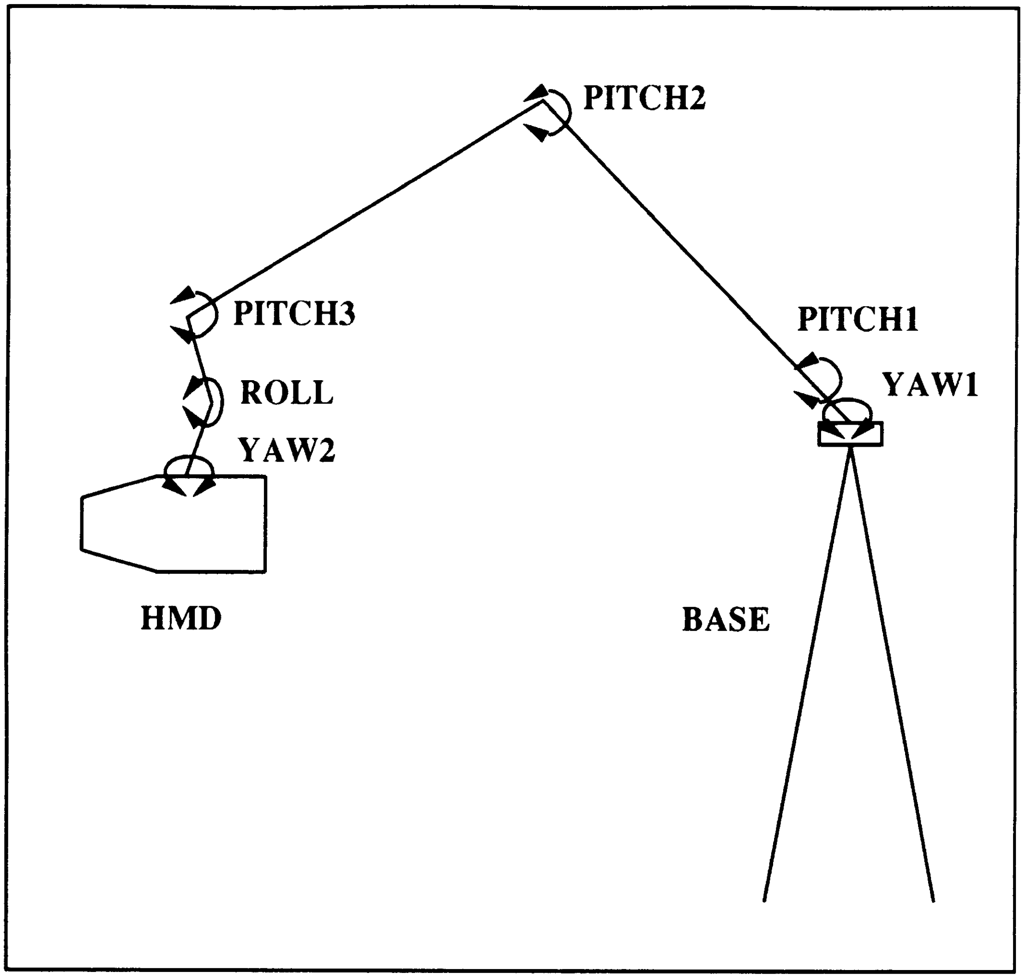

Figure 2-3: **Head Tracking Device**

rotation angles at each joint and are proportional to the output voltage of the pots. Since the stereo camera pair mounted on the teleoperated and simulated vehicles is given only rotational freedom, only the Euler angles representing the operator's head are of interest. Control station software takes the six pot readings to compute Euler angles and thus provide camera orientation commands. Although the control order is a variable, to correspond to operator expectation, the camera orientation is proportional and exactly equal to the head orientation of the operator.

A custom designed input/output (I/O) box provides the electronic interface between the joysticks and head tracker and the control station computer. The I/O box supplies voltage to the joysticks and to the potentiometers of the head tracker and routes the 12 total voltage signals from the control devices. A single cable from the I/O box connects to an Analog-to-Digital converter (ADC) board in the control station computer. The ADC is an Industrial Computer Source twelve bit, sixteen channel device (PC-74).

The control station computer is a 20 MHz 80386 Gateway PC running the multitasking QNX (version 4.0) operating system. The purpose of the system is to convert voltages from the control devices to digital signals which represent the operator's desired control commands to the teleoperated vehicle. When this system is used for the teleoperated robot STAR, command values are input to a software feedback control system, whose output commands are effectively converted to analog signals which command the thrusters. In the teleoperation simulator implementation, command values in digital form are used in the dynamic simulation of the robot. There is no need for conversion to an analog output. Control station software sets up the ADC and opens a serial communication to a Silicon Graphics IRIS 4D/25 workstation, which performs all computations. The program polls the ADC channels, computes control values and converts them to integer form for serial transport. When requested by the IRIS, these values are sent. The microcomputer communicates with the workstation across the serial connection at 38400 baud. While the IRIS primarily receives data, it must also send a synchronizing message to the Gateway each time it updates the dynamics and display to indicate that it is ready to receive the next batch of command data.

What remains in the simulation is to use the command values from the joysticks and head tracker to continually compute the state of the remote vehicle and then to update the camera view presented to the operator. The Silicon Graphics workstation which performs these computations is equipped with hardware to rapidly perform graphical transformations and with libraries of graphical subroutines tailored for three-dimensional graphics. The following sections detail the form of the computer model and the specifics of the simulation.

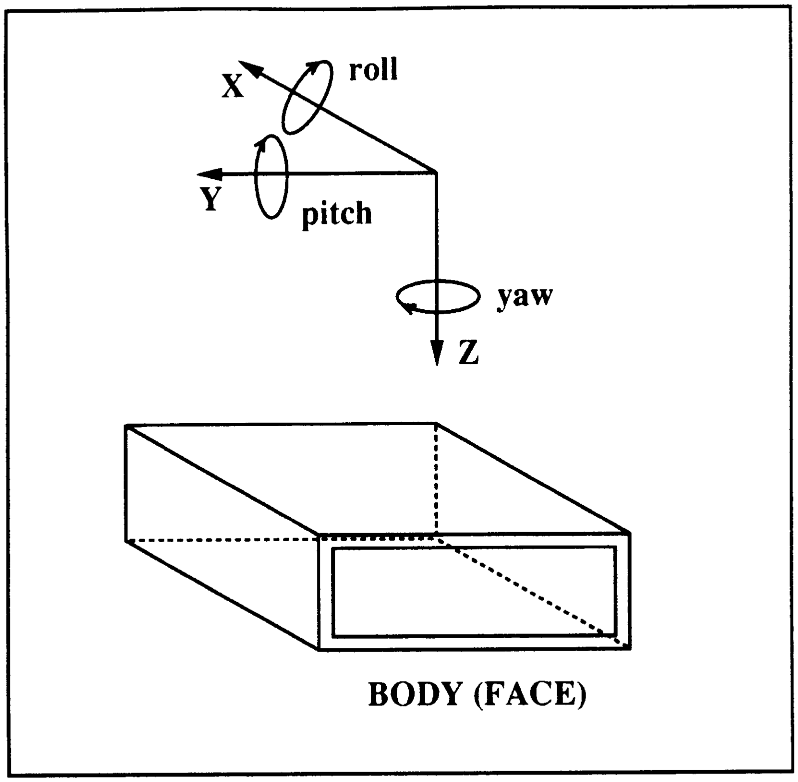

Figure 2-4: **World and Body Reference Frames**

2.3 Vehicle Dynamics

The simulated teleoperated vehicle may be programmed to observe almost any system of dynamics. A free-flying teleoperated robot in space is capable of motion in six dof and uses thrusters to accelerate in each direction. It is first necessary to define the frame of reference of the vehicle, called the world coordinate frame (Figure 2-4). This is a left hand coordinate system, although the rotation axes are right handed. The vehicle body is shown in the figure, with it's front face oriented in the negative X direction. The body frame of reference is identical to the world frame in this nominal orientation, although the body frame remains fixed with respect to the vehicle.

The control order relates how the force or deflections applied on the joysticks affect the motion of the vehicle. The translational controls are second order while the rotational controls are first order with lag. Thus translational accelerations and rotational velocities are proportional to joystick displacements. A state vector includes all variables describing the state of the vehicle. These variables are:

- x_w, y_w, z_w - position (world reference frame)
- $\dot{x}_w$, $\dot{y}_w$, $\dot{z}_w$ - velocity (world frame)
- $\dot{x}_b$, $\dot{y}_b$, $\dot{z}_b$ - velocity (body frame)
- α, β, γ - roll, pitch, yaw Euler angles (world frame)
- $\dot{\alpha}$, $\dot{\beta}$, $\dot{\gamma}$ - Euler angle velocities (world frame)
- ω_α, ω_β, ω_γ - roll, pitch, yaw rotational velocities (body frame)
- $\dot{\omega}_\alpha$, $\dot{\omega}_\beta$, $\dot{\omega}_\gamma$ - rotational accelerations (body frame)

Other variables used in the dynamics are:

- m - vehicle mass (500 kg)
- I - moment of inertia (about each axis) (3000 kg·m^2)
- dt - time step
- c_x, c_y, c_z - joystick translational deflections (range of -1...1)
- c_α, c_β, c_γ - joystick rotational deflections (-1...1)
- α_h, β_h, γ_h - head orientation angles (body frame)
- F_{max} - force at maximum joystick deflection (1200 N)
- T_{max} - torque at maximum joystick deflection (600 N·m)
- K_ω - rotational control sensitivity (0.0025 (N·m·s)$^{-1}$)
- K_l - rotational control gain constant (10000 N·m)

The equations of motion for full six DOF dynamics will now be described. Body frame accelerations are derived from command values through joystick deflections.

$$\begin{pmatrix} \dot{x}_b \\ \dot{y}_b \\ \dot{z}_b \end{pmatrix} = \frac{F_{max}}{m} \begin{pmatrix} c_x \\ c_y \\ c_z \end{pmatrix}$$

$$\begin{pmatrix} \dot{\omega}_\alpha \\ \dot{\omega}_\beta \\ \dot{\omega}_\gamma \end{pmatrix} = \frac{K_l}{I} \begin{pmatrix} K_\omega \cdot T_{max} \cdot c_\alpha - \omega_\alpha \\ K_\omega \cdot T_{max} \cdot c_\beta - \omega_\beta \\ K_\omega \cdot T_{max} \cdot c_\gamma - \omega_\gamma \end{pmatrix}$$

The Euler angle rates of change are obtained from current Euler angles and body frame rotational velocities.

$$\begin{pmatrix} \dot{\alpha} \\ \dot{\beta} \\ \dot{\gamma} \end{pmatrix} = \begin{pmatrix} \omega_\alpha + \omega_\beta \sin(\alpha)\tan(\beta) + \omega_\gamma \cos(\alpha)\tan(\beta) \\ \omega_\beta \cos(\alpha) - \omega_\gamma \sin(\alpha) \\ (\omega_\beta \sin(\alpha) + \omega_\gamma \cos(\alpha))/\cos(\beta) \end{pmatrix}$$

World frame accelerations are derived from body frame accelerations and Euler angles.

$$\ddot{x}_w = \begin{pmatrix} \dot{x}_b & \dot{y}_b & \dot{z}_b \end{pmatrix} \begin{pmatrix} \cos(\beta)\cos(\gamma) \\ \sin(\alpha)\sin(\beta)\cos(\gamma) - \cos(\alpha)\sin(\gamma) \\ \cos(\alpha)\sin(\beta)\cos(\gamma) + \sin(\alpha)\sin(\gamma) \end{pmatrix}$$

$$\ddot{y}_w = \begin{pmatrix} \dot{x}_b & \dot{y}_b & \dot{z}_b \end{pmatrix} \begin{pmatrix} \cos(\beta)\sin(\gamma) \\ \sin(\alpha)\sin(\beta)\sin(\gamma) + \cos(\alpha)\cos(\gamma) \\ \cos(\alpha)\sin(\beta)\sin(\gamma) - \sin(\alpha)\cos(\gamma) \end{pmatrix}$$

$$\ddot{z}_w = \begin{pmatrix} \dot{x}_b & \dot{y}_b & \dot{z}_b \end{pmatrix} \begin{pmatrix} -\sin(\beta) \\ \sin(\alpha)\cos(\beta) \\ \cos(\alpha)\cos(\beta) \end{pmatrix}$$

The state variables are then incremented according to their rates of change and the time step.

$$\begin{pmatrix} \dot{x}_w \\ \dot{y}_w \\ \dot{z}_w \end{pmatrix} += \begin{pmatrix} \ddot{x}_w \\ \ddot{y}_w \\ \ddot{z}_w \end{pmatrix} dt$$

$$\begin{pmatrix} x_w \\ y_w \\ z_w \end{pmatrix} += \begin{pmatrix} \dot{x}_w \\ \dot{y}_w \\ \dot{z}_w \end{pmatrix} dt$$

$$\begin{pmatrix} \omega_\alpha \\ \omega_\beta \\ \omega_\gamma \end{pmatrix} += \begin{pmatrix} \dot{\omega}_\alpha \\ \dot{\omega}_\beta \\ \dot{\omega}_\gamma \end{pmatrix} dt$$

$$\begin{pmatrix} \alpha \\ \beta \\ \gamma \end{pmatrix} += \begin{pmatrix} \dot{\alpha} \\ \dot{\beta} \\ \dot{\gamma} \end{pmatrix} dt$$

The result of these dynamic computations is a vehicle position and orientation in the world frame of reference at each time step. This is one of the functions of the simulation program running on the Silicon Graphics workstation. The simulation program structure is shown in the following pseudocode:

```
start:
    initialization and setup
    loop:
        receive operator commands from control station
        perform dynamics computations
        integrate dynamics
        perform graphical transformations
        update display
        record data for post-processing
        increment time
    until stop time.
end.
```

The time to complete a single loop through the simulation relates directly to the frame rate of the graphical display. The simulation runs in real-time, using actual operator commands.

2.4 Graphics and Display Considerations

Having computed the world frame positions and orientations of the vehicle and other objects in the environment, the virtual environment must now be updated and displayed. Graphical transformations convert world reference frame coordinates to graphical reference frame coordinates. The Silicon Graphics graphics library allows graphical coordinates to be expressed in a right hand three space coordinate system. The world and graphical reference frames are shown in Figure 2-5. The graphical transformations are:

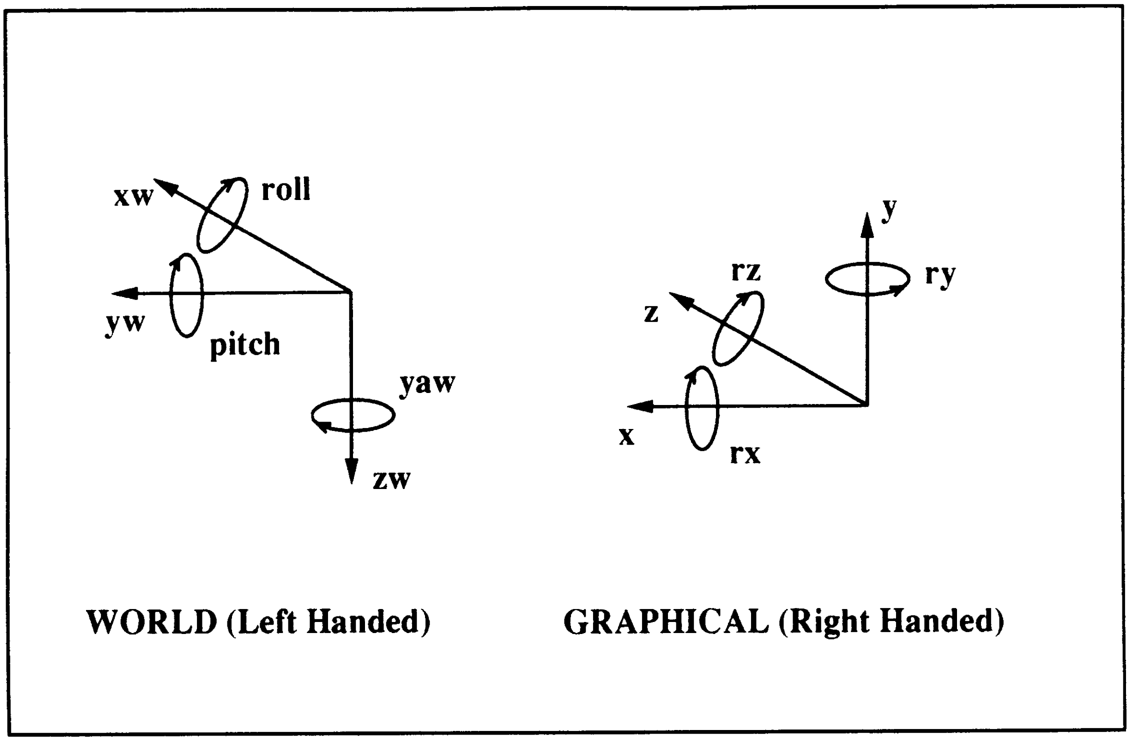

Figure 2-5: **Graphical Transformations**

$$\begin{pmatrix} x & rx \\ y & ry \\ z & rz \end{pmatrix} = \begin{pmatrix} y_w & \beta \\ -z_w & -\gamma \\ x_w & \alpha \end{pmatrix}$$

These values are used directly by the drawing routines to render a screen image to be displayed on a monitor.

One of the most significant parameters in the simulation is the time step dt, a predetermined value passed to the program. Its role is to ensure that the main program loop takes the same amount of time to execute each iteration. Under the multitasking UNIX operating system, execution speed may vary, causing undesired effects, such as variations in the screen update rate. A time step was chosen such that all computations and a full screen update could occur every cycle. The resulting update frequency of 20 Hz was found quite acceptable for the display configurations tested, meaning that flicker was not noticeable. Only monochrome wire-frame images with few objects were capable of being displayed under this time limitation. Complex scenes were not possible due to the number of graphical transformations and rendering time required.

Two video display configurations were chosen for the virtual environment simulator. A single NTSC 20-inch black and white monitor was used as a monoscopic display. The monitor was capable of a resolution of 640 $\times$ 480 pixels and was positioned approximately one meter in front of the operator. Anti-aliasing, which smooths the appearance of lines and edges, was used to achieve a larger effective resolution. A VPL EyePhones head mounted display was used to present stereoscopic images. The EyePhones consist of a pair LCD screens set, with viewing optics, directly in front of each eye. The screens have resolution of 360 $\times$ 240 pixels, with a field of view of 80° horizontal by 60° vertical per eye. The net field of view is roughly 120° horizontal while the overlap in the field of view permits stereoscopic images to be displayed. The EyePhones receive a split video signal from the workstation, with the left eye receiving the red signal and the right eye the blue. The two images are presented in white against a black background. The workstation draws both images simultaneously, with a slight offset and rotation in perspective to create a stereoscopic view. This perspective transformation is adjusted for each operator by measuring and allowing for the subject's interocular distance. The details of the graphical transformations required for stereoscopic images are included in the VPL instruction manual.[7]

Chapter 3

Experiment Design

The teleoperation simulator is the framework for the design and implementation of virtual environments for experimentation. The structure of the simulator allows great flexibility in the parameters of the simulation, although there is a limit to the complexity and richness of the visual environment. This chapter describes the considerations in environment design, the choice and implementation of various factors and the design of a teleoperation task for performance by teleoperators. The purpose of experimentation is to test teleoperator strategy and performance under each display configuration.

3.1 Virtual Environment Design

The virtual environment teleoperation simulator described in Chapter 2 is a platform for simulation and experimentation. The remote vehicle is modelled as a free-flying robot capable of motion in 6 dof. Motion is controlled by thruster commands initiated by joystick deflections at the control station. Thus, there are few limitations to the virtual environment in which the vehicle exists. Also, the vehicle dynamics can be narrowed down or tailored to the chosen environment. This section describes some of the considerations in environment design, including previous work in similar areas.

There are two approaches to designing a virtual environment task for teleoperation. The first is to look at typical teleoperation tasks and the second is to consider environments and tasks which emphasize the research objectives of this study. Considerations in human factors design play an important role in these decisions. Some typical tasks in teleoperation, such as teleoperation with the free-flying robot STAR, include flying through short trajectories, visually aquiring and navigating around targets and objects, station keeping and telemanipulation. In space, teleoperation may be used in space station construction or activities. Free-flying activities may require that the operator, positioned at a way station, aquire the next station visually and fly to it, avoiding any obstacles present.

The second requirement in virtual environment design is to construct an environment and tasks which are robust for testing to satisfy the primary research issue: how does operator performance and strategy depend upon the visual interface. Thus the design must have features which specifically address the properties of the display configurations (monitor, head mounted stereoscopic display with and without head tracking). The practical uses and advantages of each configuration are prime consideration.

A stereoscopic display is useful for presenting depth and a wide field of view and head tracking is useful for changing camera orientations and effectively providing a wider visible range. Stereoscopic displays are probably more appropriate for dextrous activity. The advantages of stereo vision for humans are most noticeable in dextrous activities; the effectiveness of stereoscopy declines rapidly beyond several meters. One advantage of stereo vision is in conveying both direction and speed of motion of objects within a short range of sight. Based on these observations, stereoscopy might be extremely useful in teleoperation requiring free-flying within a confined environment, where obstacles and objects constrain the possible trajectories of the robot. In such a situation, head tracking could be useful in aquiring these objects within a wide range of view. While controlling the motion and orientation of the vehicle, with head tracking, a human operator is free to turn their head and observe the environment. In a three dimensional environment, it is adequate to only give two free directions of motion, namely pan (left-right rotation) and tilt (up-down rotation). The benefits of stereoscopic displays and head tracking have been investigated [3, 19, 11, 14, 13, 18, 5] in order to consider issues of performance, telepresence and stereoacuity as well as human factors issues.

With the addition of the body representation, there are six possible display configurations. Specifically, these are:

1. monitor display
2. monitor with body representation
3. head mounted display
4. head mounted with body representation
5. head mounted with head tracking
6. head mounted with head tracking and body representation

The experimental design incorporates each configuration. These configurations allow each factor to be isolated for examination.

The choice of environment closely relates the system design considerations to the experimental requirements. Ultimately, experimental tasks must be designed for human subjects in order to test the hypotheses. The basic framework is a free-flying robot capable of six dof motion in a three dimensional environment. Previous studies[1, 10] found that environments based in three dimensional space with six dof dynamics made vehicle control extremely complicated, resulting in high variability in subject performance in experiments. It also seems likely the such an environment provides redundant dof's which simply divert operator attention or increase workload excessively. Such complexity also increases the learning period. The first goal of environment design is thus to consider reducing both paramaters of dof and dimensionality.

To encourage head tracking, at minimum, a planar environment is required with several dof for the vehicle. Inertial dynamics in a plane allow the vehicle to move freely, independent of the nominal "front" of the vehicle and of the operator's viewing orientation. Thus, the dynamics are simplified to allow the operator to control translational accelerations in two orthogonal directions in the x-y ground plane and to control rotational velocity about the vertical (yaw) axis of the vehicle. Refering back to the control station joystick configuration, the left hand joystick provides the two translational commands (left-right, forward-backward) while the right hand provides the single yaw rotational command.

The choice of teleoperation task depends on a number of factors, some listed here. Experimentation with human operators consisting of a series of short tasks performed under various combinations of display configurations should provide a suitable number of trials and test conditions for analyzable experimental results. Preliminary testing indicated that individual tasks longer than two minutes resulted in performance deterioration and were less amenable to analysis. Several studies have also found that many short, well defined time trials provided superior results.[12] To encourage and balance the use of all three dof, the task was expected to involve significant control and motion in a plane, with the addition of either stationary or moving obstacles or targets. Dextrous or precise teleoperation tasks require significant graphical detail (beyond the rendering capabilities of the system for the required frame rate) and do not make full use of the display configurations. A tracking task was chosen over an obstacle course or target aquisition task for a number of reasons. First, obstacle course tasks introduce the absolute parameters of distance and time. For instance, distance between targets in a virtual environment has little relation to actual distances in a true environment. Measurements of times to complete a task result in large variances among results. Unless the task is tightly constrained, time and distance measurements may not provide significant relative comparisons. A tracking task however is more amenable to analysis, particularly when analyzing manual control strategies.[15] Data from Machlis[10] also indicates that when subjects follow a slalom course with a known number of posts, performance at the start and at the end is better than in between, possibly attributable to a decrease in mental workload at these stages when the operator has a clearer idea of how much of the task remains.

The task is defined as the scenario, system behaviour and performance requirements when a human operator is placed into the simulation. The system behaviour depends upon predetermined parameters, but the operator is required to satisfy a number of explicit performance requirements using the available controls. Operators must be able to reach and sustain stable skill and performance, despite individual differences. There must be no significant improvement or deterioration over a session or between sessions once learning has been achieved. Tasks must not be predictable and, when a number of them are used, they must have minimal correlation. In effect, the design must attempt to minimize many of the nonlinear characteristics of the operator's control strategy and of the simulation. These include the following:

- threshold - smallest magnitudes preceivable
- saturation - maximum control possible
- dither - high frequency, low amplitude control technique
- range effect - overrespond to smaller, underrespond to larger than average input
- preview - predict input signal
- attention or fatigue - deterioration of performance
- optimizing techniques[9]

It is also important to eliminate or balance any task characteristics which enhance or favour a particular directional bias. Data from Machlis[10] indicates that in the slalom tasks, each subject showed a performance improvement in one direction which does not appear related to handedness although may be related to the joystick configuration used.

The virtual environment selected for experimentation is shown in Figure 3-1. The environment consists of a plane where the teleoperated vehicle is free to rotate and translate in two directions. The major difficulty of the design is representing a plane with wireframe images. To maintain a suitable frame rate, only a limited number of polygonal wireframe images can be included. Implementation of a ground grid consisting of parallel lines is very distracting and difficult to discern. Motion along such a grid does not convey an adequate impression of visual flow, including direction and

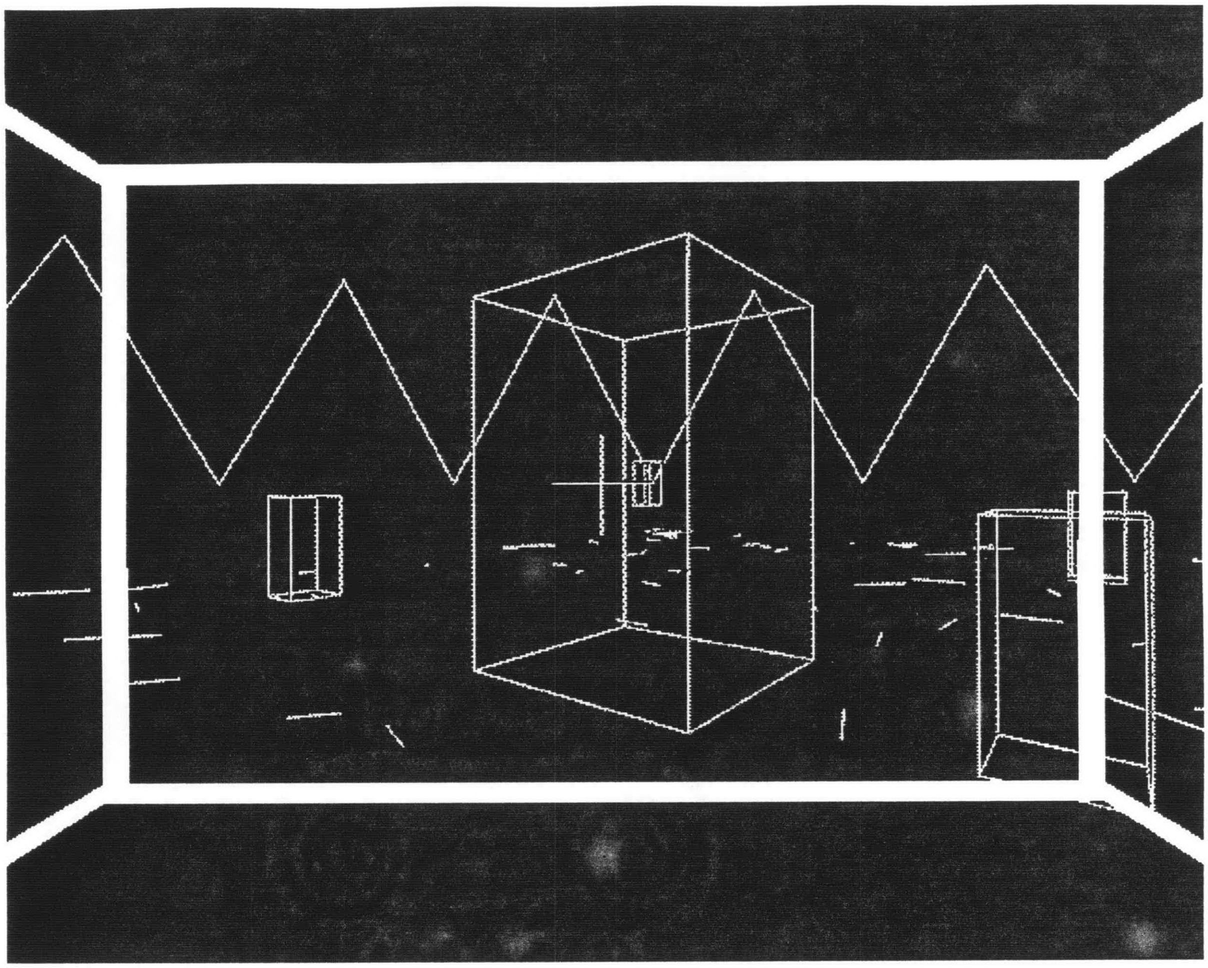

Figure 3-1: **Planar Virtual Environment with Moving Target, Obstacles, Body Representation, Ground Sticks and Mountain Range**

rate of motion. Instead, the plane is highlighted with the use of randomly oriented short "sticks" scattered throughout. These figures provided a superior impression of motion to teleoperators. Another alternative, to use pinpoint stars in the sky as visual cues is not particularly useful in this planar environment. The environment is encircled by a periodic sawtooth "mountain range" at some distance. This conveys a sense of rotational direction and velocity as the vehicle moves throughout the environment.

Having designed and implemented a virtual environment for teleoperation, the specifics of the moving target tracking task can be addressed. The moving target is a wireframe cube with an identical but smaller cube located at its center. This target moves throughout the planar environment and is visible at both near and far distances. The pattern of motion will be discussed shortly. As can be seen from the figure, the perspective view of the target varies with the angle and distance of observation from the teleoperated vehicle. The tracking task requires the operator to satisfy a number of goals such as to control the motion and orientation of the vehicle so as to follow the moving target. To prevent operators from adopting simple linear tracking strategies, a number of stationary obstacles were introduced to the environment for each tracking task. The dispersion of obstacles should also encourage head tracking when available in order to observe and avoid hitting obstacles.

The remaining objects of interest shown in the figure are the vehicle body representation and the centered crosshairs. The vehicle body frame is a solid outline of the front of the teleoperated vehicle which remains fixed relative to the body of the vehicle. It's purpose is to provide the operator with information as to the relative orientation of the vehicle body with respect to their direction of view (particularly in the case of head tracking) and to the direction of motion. The centered crosshairs may allow for more accurate tracking. The addition of these cues is a significant consideration in virtual environment teleoperation in attempting to improve the operator's concept of position and orientation. As such, these cues have been incorporated as a variable in the study.

Target trajectories specify the exact patterns of motion over time, specifically the target position at each instant. A number of factors were considered in designing the target trajectories. First, the motions and accelerations must be somewhat smooth but unpredictable. This was achieved by forming trajectories from three periodic waveforms of varying amplitudes, frequencies and phases, with higher frequency components having smaller amplitude. To obtain relatively smooth accelerations, sinusoids were used for a number of trajectories. For sharper accelerations, sawtooth waves were used for an equal number. Stationary obstacles were placed in the plane strategically near the trajectory. The trajectory patterns are shown in Appendix A. The view is from above the plane of the environment, looking down. The remote vehicle is initially located at the center of the grid facing north (top of the page). The smaller boxes are obstacles, and the path is that of the target, with the larger box showing it's initial position. To eliminate a tendency for subjects to favor rotating their vehicle in one direction when they lose sight of the target, trajectories were designed in symmetrical pairs, being right-left (east-west) mirror images of each other. A total of six target trajectories were designed, each with a mirror image.

3.2 Experimental Procedure

The experimental procedure incorporates each of the display configurations and uses a number of specific instances of the tracking task described in the previous section. Each human subject follows identical experimental stages. To avoid simulator sickness and deteriorating performance, preliminary tests were done to determine an approximate session length of 45 minutes with runs not longer than two minutes. For each of the six configurations, at least one session of specific learning would be required and is provided, with cross learning of the environment and task occurring progressively. Thus the experiment design includes a total of three sessions per configuration, taking place over six closely spaced days. On each day, the subject performs under three of the six monitor configurations, with six runs per configuration, each run based on one of the six target trajectories (or their images). With each run taking 90 seconds with 30 seconds of rest between runs, each configuration requires 12 minutes, and with 3 minutes rest between configuration, each session lasts 42 minutes.

The experimental matrix (Figure 3-2) provides the full details of the setup for all sessions. To interpret this table, follow this example: on day 3 of experimentation, in the first of 3 slots of the day, the subject uses the display configuration (Con=4) of hmd with body representation for the first six runs of that day. The six target trajectories used in these six runs are in the order given by the first trajectory set (TSet=1). The order of trajectories is 1,4',5',3,2',6, where the prime (') indicates the mirror image trajectory. The balancing of experimental factors or variables is based primarily on a latin square design, although there are too many factors for a complete design in the number of sessions available. The subjects perform under all six display configurations over three pairs of consecutive days (1-2, 3-4, 5-6). If learning occurs over all six days, rather than over the anticipated first two days, grouping of at least consecutive days is possible. Each display configuration also occurs in each of the three slots in a day. If learning or performance degradation does occur on a single day, this balancing should demonstrate and account for it. Finally, within each day, only one of each similar configuration pair (1-2, 3-4, 5-6) is used. Performance in a given day under indentical configurations with and without the body representation could create an asymmetrical transfer. That is, performing under the first of the pair affects subsequent performance under the second. Thus each day includes three dissimilar display configurations. There were numerous ways to design the experimental matrix. This choice was expected to anticipate and account for some of the major factors affecting performance.

Subjects perform six runs under each of the three display configurations in a given day. The gouping of these six runs is called a trajectory set. There are six total trajectory sets, each including all six target trajectories (either the normal or mirror image). Trajectory sets occur in pairs; sets one and two include all six trajectories and their images only once. In a given day, one trajectory set from each of the three pairs is used in each of the three slots. On the second of the paired day, the other three sets are used. The reason for the choice of six target trajectories and the design of six run sets is to prevent subjects from mastering a small number of runs and from remembering the order in which runs occur.

The experimental design attempts to isolate each of the significant factors and to enable valid comparisons between similar factors. The technique of balancing tries to keep all factors identical but one, the factor of interest. The major comparisons are between monitor and head mounted display, body and no body representation, and hmd with and without head tracking. Secondary considerations include performance under the target trajectories and their images, between day comparisons, within day comparisons, and within slot (configuration) comparisons.

While the design balances known and anticipated factors, there are a number

Experimental Matrix

Slot	Day 1 Con	Day 1 TSet	Day 2 Con	Day 2 TSet	Day 3 Con	Day 3 TSet	Day 4 Con	Day 4 TSet	Day 5 Con	Day 5 TSet	Day 6 Con	Day 6 TSet
1	1	1	3	6	4	1	2	3	6	1	5	3
2	4	3	5	2	6	6	3	5	2	6	1	5
3	6	5	2	4	1	2	5	4	3	4	4	2

Display configuration (Con)

Con	Display	Body Representation	Head Tacking
1	monitor	0	0
2	monitor	body	0
3	hmd	0	0
4	hmd	body	0
5	hmd	0	track
6	hmd	body	track

Trajectory Sets (TSet)

TSet	Trajectory Order 1	2	3	4	5	6
1	1	4'	5'	3	2'	6
2	2	3'	6'	4	1'	5
3	4'	5	3'	1	6	2'
4	3	6'	2	5'	4	1'
5	6'	1	4'	2'	5	3
6	5'	2	1'	6	3'	4

Figure 3-2: **Experimental Matrix**

operator specific factors to be considered. Three human subjects were chosen for experimentation. These were three male students, ages 19 to 24. The most significant similarity was their previous experience with the teleoperation control station as it was implemented with STAR. The subjects were comfortable with the type of control provided by the pair of joysticks. They had clear concepts regarding teleoperation, specifically that of controlling a remote vehicle with a forward mounted camera whose image is presented in real-time on a monitor display. These factors also contributed to motivating these subjects. The following paragraphs describe the experimental procedure.

Subjects were administered a preliminary questionnaire and test to ascertain a number of factors, specifically regarding handedness, vision and experience. The questionnaire and results are included in Appendix B, with a brief summary presented here. All subjects had perfect vision, although they showed varying degrees of eye-handedness. None showed serious advantages due to experience. The physical well-being of the subjects prior to, during and following experiments were major considerations. None demonstrated or expressed any physical characteristics which could limit their performance. On each day, a questionnaire was administered before and after the session to determine physical dispositions and deteriorations. This was an attempt to gauge susceptibility to simulator sickness and whether the sessions were too long. The primary factor which changed during the session was tiring and soreness of eyes, although on the scale used (one to five representing none to much), the degree change was never severe (never greater than a change of two levels). Thus little subject variability accountable to physical deterioration during sessions is anticipated.

Subjects perform a moving target tracking task in a planar environment with obstacle avoidance. The choice and expression of tracking goals relate directly to the performance metric used in evaluation and analysis. This type of tracking task can be accomplished through two extreme strategies. The first is simple translational tracking, involving moving left-right and fore-aft in order to minimize distance to the target. The other extreme is yaw tracking in which the operator commands rotation in order to keep the target in sight at all times. Head tracking is expected to aid the first strategy, particularly with obstacles, while the affect on the second strategy is uncertain. A requirement to avoid obstacles is expected to prevent operators from completely adopting the first strategy both with and without head tracking. A requirement to minimize distance from the target prevents adoption of the second strategy. Requiring that the vehicle body face the target will generally ensure the use of rotational control in addition to translation. And finally, the operators are instructed to be moving towards the target so that obstacle avoidance is actually required. The instructions to the experiment, as presented to the subjects is included in Appendix C. The tracking goals, of equal importance are:

1. Always be as close to the target as possible.
2. Always be moving towards the target.
3. Always have your vehicle body facing the target.
4. Never hit an obstacle.

Clearly there is no strategy which can completely satisfy all goals. Operators must adopt a robust strategy, perhaps sacrificing some performance in one goal to maintain acceptable performance in another.

The protocol for each experiment session (each day) was to administer the pretest questionnaire, remind the operator of the four tracking goals, and to prepare the operator prior to using each display configuration by reminding them which display factors were in effect and which were not (monitor or hmd, body representation, and head tracking). Between each run, subjects did not remove the hmd. They did remove the device in the two periods between display configurations. The room was illuminated by a very dim, covered light in all cases.

The following chapter describes the form of the data obtained from the experiments and the reduction of this data to a small number of performance metrics. The next chapter describes the analysis and results derived from the experiment.

Chapter 4

Data Processing

The previous chapter describes the experimental design and procedures. This chapter describes the form of the data derived from the experiments and the processing of this data. The objective of data processing and analysis is to obtain a small number of performance metrics from the large amount of data. These metrics must relate closely to the tracking goals as stated to the subjects. Statistical analysis of this data, presented in the following chapter, tests the hypothesis of performance and control strategy differences due to the experimental variables.

4.1 Performance Metrics

The experimental design makes it possible to save all state data in order to fully reconstruct each run and to perform post-processing. Because each run requires exactly 90 seconds, a 20 Hz frame rate results in 1800 iterations or loops through the computer program. At each iteration, data is saved to a file. The components of this string of data per iteration are the following:

- *loop* or i - loop/iteration number (1-1800)
- x_t, y_t - moving target coordinate position (world frame)
- x_o, y_o - obstacle coordinate positions (10 obstacles) (world frame)
- x_v, y_v - vehicle position (world frame)

- γ - yaw Euler angle (world frame)

- $\dot{x}_v$, $\dot{y}_v$ - vehicle velocity (world frame)

- $\dot{\gamma}_b$ - vehicle yaw rotational velocity (body frame)

- f_{x_b}, f_{y_b} - translational force commands (body frame)

- t_{γ_b} - yaw torque command (body frame)

- γ_h, β_h - head orientation angles (body frame)

- $loop_{hit}$, $x_{o_{hit}}$, $y_{o_{hit}}$ - loop and position when an obstacle is hit

This data provides a complete description of the run sufficient to reproduce all operator inputs, vehicle responses and target positions. This feature is valuable when trying to reconstruct actions and strategies taken by the operators at run time. Figure 4-1 is included to demonstrate the form of the data file obtained from one sample run. Each line is the string of data saved during one iteration of the simulation loop (Section 2.3).

Deriving performance metrics from the volume of data which constitutes a run is an iterative task. There are numerous ways to relate the data to the tracking goals expressed to the operators. A number of options are described here. These metrics relate the saved data and the tracking task geometry to obtain a few robust values which indicate relative performance. Statistical analysis is used to determine significant differences among each metric for the experimental variables of interest. Significant differences between variables is expected to lead to conclusions regarding performance and strategy under each experimental condition. This chapter describes the derived metrics and the following presents statistical analysis.

The following discussion makes use of the geometry of the environment and the relative positions and orientations of the vehicle and the moving target. Figure 4-2 details the significant variables in the planar world frame environment. The vehicle and its body frame are in a random orientation centered at the origin of a temporary world frame. The vehicle body frame **B** (**xb yb**) is offset by an angle θ_b with respect to

i	x_v	y_v	x_t	y_t	γ	$\dot{x}_v$	$\dot{y}_v$	$\dot{\gamma}$	f_x	f_y	t_z	γ_h	β_h
0	0	0	-20	-20	0	0	0	0	0.0	0.0	0.0	0	0
1	0	0	-19.86	-20.05	0	0	0	0	0.0	0.0	0.0	0	0
2	0	0	-19.72	-20.11	0	0	0	0	0.0	0.0	0.0	2.64	1.32
3	0	0	-19.58	-20.17	0	0	0	0	0.0	0.0	0.0	2.64	1.76
4	0	0	-19.44	-20.23	0	0	0	0	0.0	0.0	0.0	3.52	1.32
5	0	0	-19.3	-20.29	0	0	0	0	0.0	0.0	0.0	3.52	1.32
6	0	0	-19.17	-20.36	0	0	0	0	0.0	0.0	0.0	3.52	1.32
7	0	0	-19.03	-20.43	0	0	0	0	0.0	0.0	0.0	2.64	0
8	0	0	-18.9	-20.51	0	0	0	0	0.0	0.0	0.0	1.76	1.32
9	0	0	-18.76	-20.59	0	0	0	0	0.0	0.0	0.0	1.76	1.32
10	0	0	-18.63	-20.68	0	0	0	0	0.0	0.0	0.0	2.64	1.32
11	0	0	-18.5	-20.77	0	0	0	0	0.0	0.0	0.0	1.76	-0.44
12	0	0	-18.38	-20.86	0	0	0	0	0.0	0.0	0.0	1.76	-0.44
13	0	0	-18.25	-20.96	0	0	0	0	0.0	0.0	0.0	1.76	-1.32
14	0	0	-18.13	-21.06	0	0	0	0	0.0	0.0	0.0	0	-0.44
15	0	0	-18.01	-21.17	0	0	0	0	0.0	0.0	0.0	1.76	-0.44
16	0	0	-17.89	-21.28	0	0	0	0.04	0.0	0.0	100.8	2.64	-0.44
17	0	0	-17.77	-21.4	0	0	0	0.12	0.0	0.0	206.6	2.64	-1.32
18	0	0	-17.66	-21.52	0.01	0	0	0.22	0.0	0.0	291.0	0	-0.44
19	0	0	-17.55	-21.65	0.02	0	0	0.33	0.0	0.0	356.0	3.52	-0.44
20	0	0	-17.44	-21.78	0.04	0	0	0.44	0.0	0.0	400.8	3.52	-1.32
21	0	0	-17.34	-21.91	0.06	0	0	0.55	0.0	0.0	432.2	0	-0.44
...	...	...	...	...	...	...	...	...	...	...	...	...	...
193	-9.5	-2.81	-1.83	-31.74	0.1	-1.86	1.17	-0.59	0.0	1005.0	-364.8	25.49	0
194	-9.59	-2.75	-1.43	-31.51	0.07	-1.87	1.27	-0.65	0.0	1006.1	-373.3	25.49	0
195	-9.68	-2.68	-1.03	-31.29	0.03	-1.87	1.37	-0.7	0.0	1012.0	-381.5	25.49	0
196	-9.78	-2.6	-0.63	-31.07	6.28	-1.88	1.47	-0.74	0.0	1006.7	-385.0	25.49	0
197	-9.87	-2.53	-0.23	-30.85	6.24	-1.87	1.57	-0.78	36.4	1012.6	-380.0	25.49	0
198	-9.96	-2.44	0.17	-30.63	6.21	-1.83	1.67	-0.8	406.1	1010.8	-355.1	25.49	0
199	-10.05	-2.35	0.57	-30.42	6.17	-1.75	1.77	-0.8	671.0	1003.2	-338.4	25.49	0
200	-10.13	-2.26	0.97	-30.21	6.13	-1.66	1.86	-0.8	793.4	1002.0	-317.6	25.49	0
201	-10.21	-2.16	1.37	-30	6.09	-1.57	1.94	-0.8	817.5	986.8	-303.9	27.25	0
202	-10.28	-2.06	1.76	-29.8	6.05	-1.46	2.02	-0.78	890.7	990.3	-290.7	27.25	0
203	-10.35	-1.96	2.15	-29.6	6.01	-1.35	2.1	-0.77	904.2	986.2	-277.8	25.49	0

Figure 4-1: **Partial Saved Data From a Sample Run**

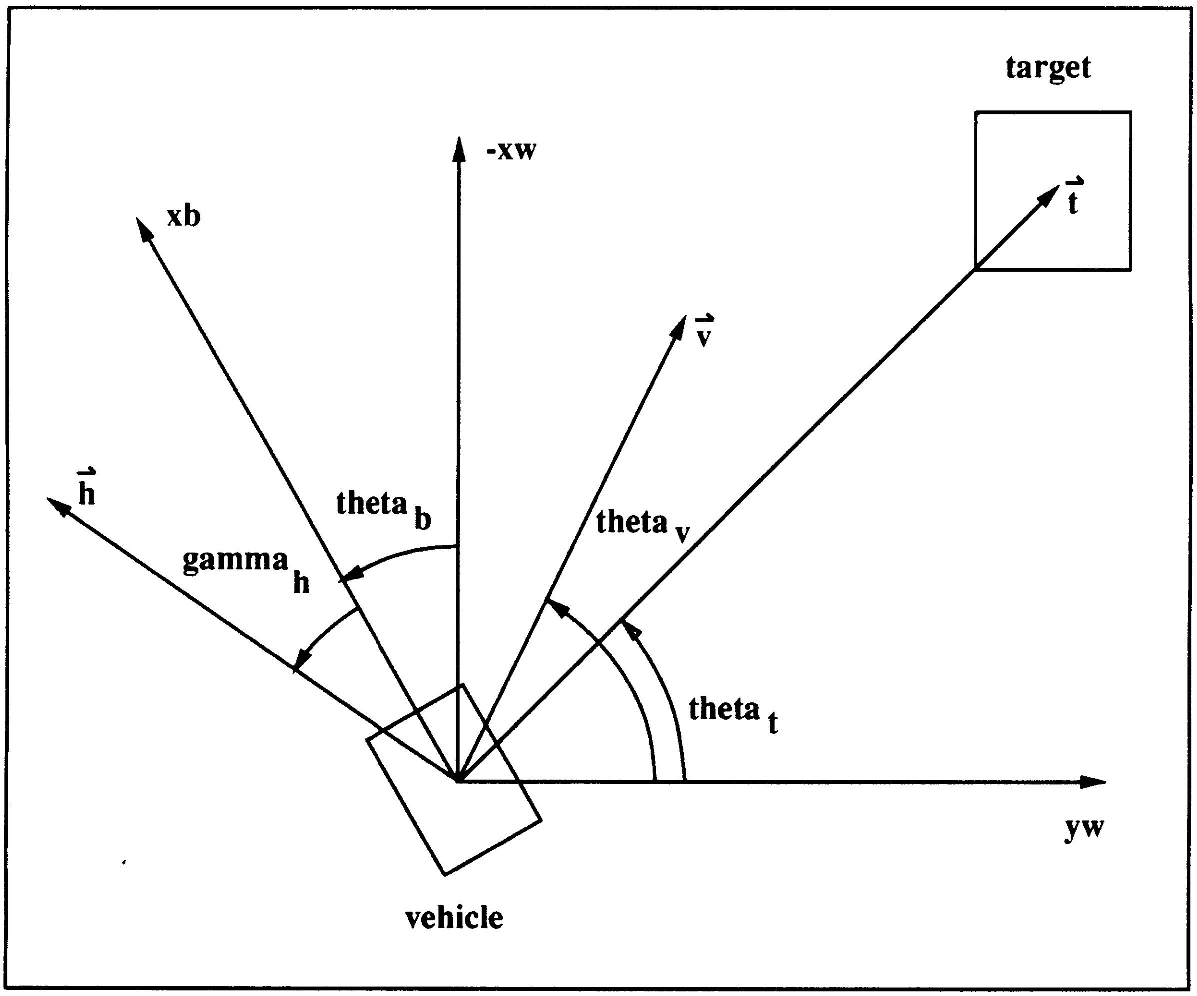

Figure 4-2: **Tracking Task Geometry**

the world frame **W** (**xw yw**). When head tracking is in effect, the angle γ_h measures the offset of the head orientation vector $\vec{h}$ (the direction of view) from the body frame axis **xb**. The vehicle moves in the velocity direction $\vec{v}$ with offset angle θ_v relative to the world frame axis **yw**. The target body frame relative to the vehicle body frame is offset by the vector $\vec{t}$, whose length is called the separation and is offset from the world frame axis **yw** by angle θ_t.

The first goal of the tracking task is to control the vehicle so that it is as close as possible to the moving target. The primary parameter of interest is the length of the vector $\vec{t}$ which is the separation between vehicle and target positions. From the saved data, this value is obtained for each of the 1800 iterations from the world frame positions of the vehicle and the target. The metric computed for each run is the mean square distance or separation, in units of meters.

The second goal expressed to the operators is to move towards the target. The velocity vector $\vec{v}$ provides direction of motion with angle θ_v. The relation of these parameters to $\vec{t}$ and θ_t provides an offset angle θ_{vt} which measures the performance with respect to this goal. Larger values of θ_{vt} indicate poorer tracking. Again, the values at each iteration in a run are of interest as well as a single computed value which defines performance for the run. However, because the metric is an angle expressed in radians, a number of considerations arise. First, when the operator commands the vehicle to perform a full yaw rotation, the offset angle θ_{vt} may, for instance, change from zero to 2π radians with both extremes being equal. Thus the metric is expressed only with magnitude in a range of zero to π radians. Another interesting situation occurs when the operator passes through or close to the target. In these situations, the offset angle θ_{vt} will change rapidly. What is typically happening, particularly when head tracking is not employed is that the operator is positioned very close to the target but does not have it in visual range for most of the event. Thus, this metric may sometimes indicate poor angle tracking when the operator is actually successfully position tracking. There are a number of additional characteristics of this offset angle which will be of interest. These will be discussed in a later section.

The third goal requires the operator to have the vehicle body facing the target, providing a similar metric to the previous. The body offset angle θ_{bt} relates the body vector to the target relative position vector. The same issues arise as to magnitude and values achieved for this angle as for the velocity offset angle. The angle θ_{bt} also has a magnitude between zero and π radians.

The fourth goal is to never hit an obstacle. The simulation saves the times and positions of all such collisions in a file. In practice, this parameter is not particularly conducive to analysis. Obstacles were introduced to prevent the adoption of extreme tracking strategies and to encourage head tracking. The number of collisions probably does not correlate closely to tracking performance because collisions are often out the operator's control. That is, not all obstacles are visible at any instant. When collisions are a result of poor tracking, the other metrics are expected to indicate this.

There are other metrics of interest in the deduction of operator control performance and strategy. When head tracking is available, the angle γ_h of head orientation with respect to the body frame is significant. This represents the direction of view of the operator with respect to the body of the vehicle, that is, straight ahead.

An additional performance metric arises in the consideration of tracking or control strategy. While there are a number of metrics which relate to tracking success as expressed by the four tracking goals, there are a number of measurements which are more relevant to strategy and control. The first is the mixture and amount of translational acceleration and rotational velocity commanded, specifically through the joysticks. The second consideration is the freqency of corrections applied in tracking. These corrections appear as changes in command values. Because the vehicle obeys inertial dynamics, absolute changes are not as important as relative changes in direction, velocity and orientation. For position tracking, changes in translational force commands are interesting. The force commands f_{x_b} and f_{y_b} saved for each iteration are the significant parameters. For angular tracking, that is, the effort to continue facing and moving towards the target, changes in yaw orientation and velocity direction relative to the target are interesting. One metric is the number of changes of the angle θ_{vt} over a run. These appear as changes in sign of the first derivative of θ_{vt}

over time. For reference, this metric is called change in direction. The other metric related to angular tracking is the yaw torque command t_{γ_b}.

4.2 Computation of Performance Metrics

The goal of post-processing the data files saved from all runs is to compute the small number of metrics which indicate performance for each run. As described in Chapter 3, each subject performs 18 runs per day over six days for a total of 108 runs. Statistical analysis, particularly analysis of variance (ANOVA) requires all variables and metrics to be tabulated for each run. This section will describe the calculations used to obtain the performance measurements from the saved data for each run (as shown in Figure 4-1). Please refer to the list of variables in section 4.1 and Figure 4-2.

The first performance measurement, as discussed in the previous section, is the average separation of the target and vehicle. For each loop or iteration i, separation is given by equation 4.1 and the average separation for a run is given by equation 4.2.

$$t_i = \sqrt{(x_t - x_v)^2 + (y_t - y_v)^2} \tag{4.1}$$

$$t_{avg} = \sum_{i=1}^{1800} t_i/1800 \tag{4.2}$$

The second metric is the average offset angle of vehicle velocity with respect to target position from the vehicle. For each iteration, θ_{vt} is simply the difference of velocity direction θ_v and target direction θ_t in the world frame. A correction is made to obtain a value of $-\pi \leq \theta_{vt} < \pi$. For the run, there are two possibilities: average value and average root mean square (rms) value.

$$\theta_{v_i} = atan2(\dot{y}_v, \dot{x}_v) \tag{4.3}$$

$$\theta_{t_i} = atan2(y_v - y_t, x_v - x_t) \tag{4.4}$$

$$\theta_{vt_i} = \theta_{v_i} - \theta_{t_i} \tag{4.5}$$

$$\theta_{vt_{avg}} = \sum_{i=1}^{1800} \theta_{vt_i}/1800 \tag{4.6}$$

$$\theta_{vt_{rms}} = \sum_{i=1}^{1800} \sqrt{\theta_{vt_i}^2}/1800 \tag{4.7}$$

The third metric relates θ_v to the body offset angle θ_b in a similar manner to obtain an angle θ_{bt} per iteration and an average and rms value for each run.

$$\theta_{bt_i} = \frac{\pi}{2} + \theta_{b_i} - \theta_{t_i} \tag{4.8}$$

$$\theta_{bt_{avg}} = \sum_{i=1}^{1800} \theta_{bt_i}/1800 \tag{4.9}$$

$$\theta_{bt_{rms}} = \sum_{i=1}^{1800} \sqrt{\theta_{bt_i}^2}/1800 \tag{4.10}$$

When head tracking is used with the HMD, the angle γ_h of head orientation offset with respect to body frame is saved for each iteration. For a run, average and rms head orientation angles are computed.

$$\gamma_{h_{avg}} = \sum_{i=1}^{1800} \gamma_{h_i}/1800 \tag{4.11}$$

$$\gamma_{h_{rms}} = \sum_{i=1}^{1800} \sqrt{\gamma_{h_i}^2}/1800 \tag{4.12}$$

There are two ways to analyze the force and torque commands. The first is to take an average value over the run, taking the directions into account. This is expected to indicate a directional bias. The second metric is the average magnitude or rms value. This indicates the net and relative amounts of forces and torque commanded by the operator. These metrics are computed as the other average (avg) and rms values.

$$f_{x_{avg}} = \sum_{i=1}^{1800} f_{x_i}/1800 \quad (4.13)$$

$$f_{x_{rms}} = \sum_{i=1}^{1800} \sqrt{f_{x_i}^2}/1800 \quad (4.14)$$

$$f_{y_{avg}} = \sum_{i=1}^{1800} f_{y_i}/1800 \quad (4.15)$$

$$f_{y_{rms}} = \sum_{i=1}^{1800} \sqrt{f_{y_i}^2}/1800 \quad (4.16)$$

$$t_{\gamma_{avg}} = \sum_{i=1}^{1800} t_{\gamma_i}/1800 \quad (4.17)$$

$$t_{\gamma_{rms}} = \sum_{i=1}^{1800} \sqrt{t_{\gamma_i}^2}/1800 \quad (4.18)$$

The experimental variables and computed performance metrics are tabulated to include every run for all subjects in a matrix format. The matrix is stored in a file for data analysis. The form of the matrix and the codes used are shown in Figure 4-3. For each run, each factor (refered to by label) is assigned a single value given by the last column in the table. There are a total of 108 rows of data for each of the three subjects. The first ten factors listed in the table completely describe the experiment setup. For each run, the values of these first ten factors are the experimental variables of interest. The remaining 15 factors are the results of the experiment. For each run, these values are the performance metrics of interest.

Factor	Label	Values Taken
subject	SUBJ	1 2 3
day	DAY	1 2 3 4 5 6
slot	SLOT	1 2 3
trajectory set	TSET	1 2 3 4 5 6
slot in trajectory set	TNUM	1 2 3 4 5 6
trajectory	TRAJ	1 2 3 4 5 6
mirror trajectory	PRIME	1 (=normal) 2 (=mirror image)
monitor	MON	1 (=monitor) 2 (=hmd)
body representation	BODY	1 (=no) 2 (=yes)
head tracking	HEAD	1 (=no) 2 (=yes)
separation	SEP	equation 4.2
velocity offset	VT	equation 4.6
rms velocity offset	VTR	equation 4.7
body offset	BT	equation 4.9
rms body offset	BTR	equation 4.10
head orientation	HT	0 (=no head tracking) else equation 4.11
rms head orientation	HTR	0 (=no head tracking) else equation 4.12
direction changes	CDT	number of direction changes
force - x direction	FX	equation 4.13
rms force -x dir	FXR	equation 4.14
force - y direction	FY	equation 4.15
rms force - y dir	FYR	equation 4.16
torque - yaw	TZ	equation 4.17
rms torque - yaw	TZR	equation 4.18
obstacles hit	HIT	integer number of hits

Figure 4-3: **Format of Matrix File for Data Analysis**

Chapter 5

Data Analysis and Results

This chapter discusses the statistical analysis of the experimental data and specifically of the derived performance metrics discussed in the previous chapter. The purpose of this analysis is to test the hypothesis that subject tracking performance and strategy are related to the experimental variables, particularly the factors of monitor and head mounted display, body representation and head tracking. The significance of performance results relative to these and other factors are tested in order to derive conclusions.

5.1 Statistical Techniques

There are two forms of data resulting from the experiments and post processing which can be examined and analyzed. Chapter 4 discusses how the raw data from experiments are converted to each of these forms. In section 4.2, the performance metrics are computed for each instant (or iteration) in a run and an average or rms value is computed for each run. In the first form, a resulting metric can be examined as a continuous variable over the 90 seconds (1800 loops) which constitute a run. In the second form, a single number represents each metric for a run. Figure 4-3 lists the 25 values which describe each run. The first ten factors in the table describe the experimental parameters completely for a run. The remaining values are the performance metrics for that run. This set of 25 values exists for all runs for all subjects. Statistical analysis is performed on this matrix file of data.

5.2 Continuous Plots

The continuous plots of the computed performance metrics over time for each run are useful for observing what actually happens as the subject tracks the target over the course of a run. Continuous plots are presented for a number of metrics in Figures 5-1 to 5-6. The following discussion highlights some of the characteristics of these plots.

A plot of separation over time shows how far the target is from the teleoperated vehicle. A sample of this plot is included as Figure 5-1. Noticeable is the fact that the separation changes smoothly, due to operator control of translational thruster (or force) commands as opposed to velocity or position. To change from decreasing to increasing separation, the operator must typically accelerate the vehicle away from the target, resulting in a smooth velocity and position change. The fact that the separation varies mostly about some mean value may indicate that the operator is trying to keep the vehicle some fixed distance from the target. In this case, the value appears to be approximately 25 meters. This strategy relates back to the tracking goals. The first goal requires the operator to minimize the distance to the target. The other goals relate to angular tracking. A robust strategy requires that the operator not get too close to the target because this leads to degradation of the angular tracking performance. Thus the operator adopts a strategy which balances these two tracking goals.

A plot of velocity offset (and of rms velocity offset) shows the direction of motion of the vehicle relative to the target over a run (Figure 5-2). When the value of velocity offset is zero, the vehicle is moving directly towards the target. When it is $\pm\pi$, the vehicle is moving away from the target. A crossover occurs at the equal values of π and $-\pi$ and vice-versa. It appears that the operator is attempting to correct velocity offset towards zero radians. This satisfies the tracking goal of moving directly towards the target. The plot of velocity offset also demonstrates the derived metric, change of

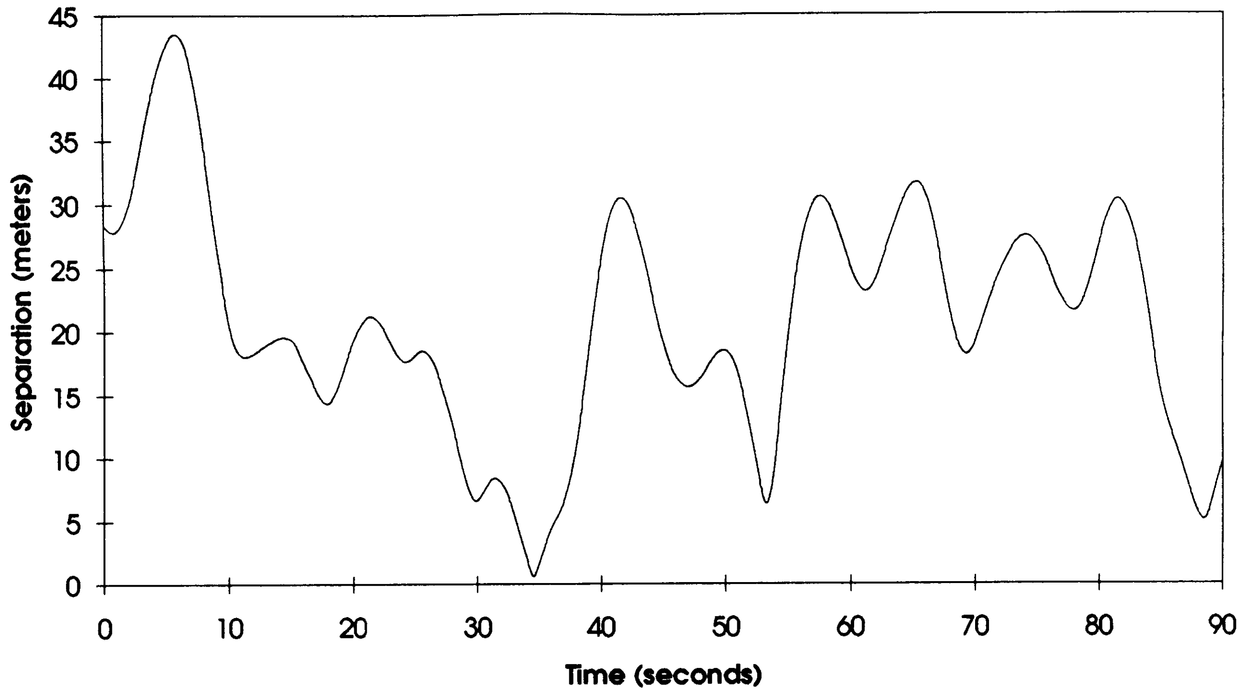

Figure 5-1: **Continuous Plot of Separation versus Time for a Run**

direction. A direction change occurs when the derivative or slope of this plots changes sign (or is infinite). For this particular run, there are 34 direction changes.

A plot of body offset (and of rms body offset) versus time shows the orientation of the vehicle body relative to the target. Figure 5-3 demonstrates that when this value reaches zero, the vehicle body is directly aligned with the target. That is, the target is centered in the body crosshairs if these are visible. It appears that the operator is attempting to correct this value towards zero, in satisfying tracking goal number three.

Plots of forces and torque versus time represent the commands (in the body frame) of the operator. They directly correlate to the corresponding joystick displacements. Over most of the run, the operator commands no forces, commanding y force less often though for longer duration per command. The plot of torque indicates that torque is commanded more frequently than forces. The fluctuations at the minimum/maximum values indicate saturation of joystick commands. It also appears that force commands are primarily maximum or zero (on-off) while torque commands vary in magnitude.

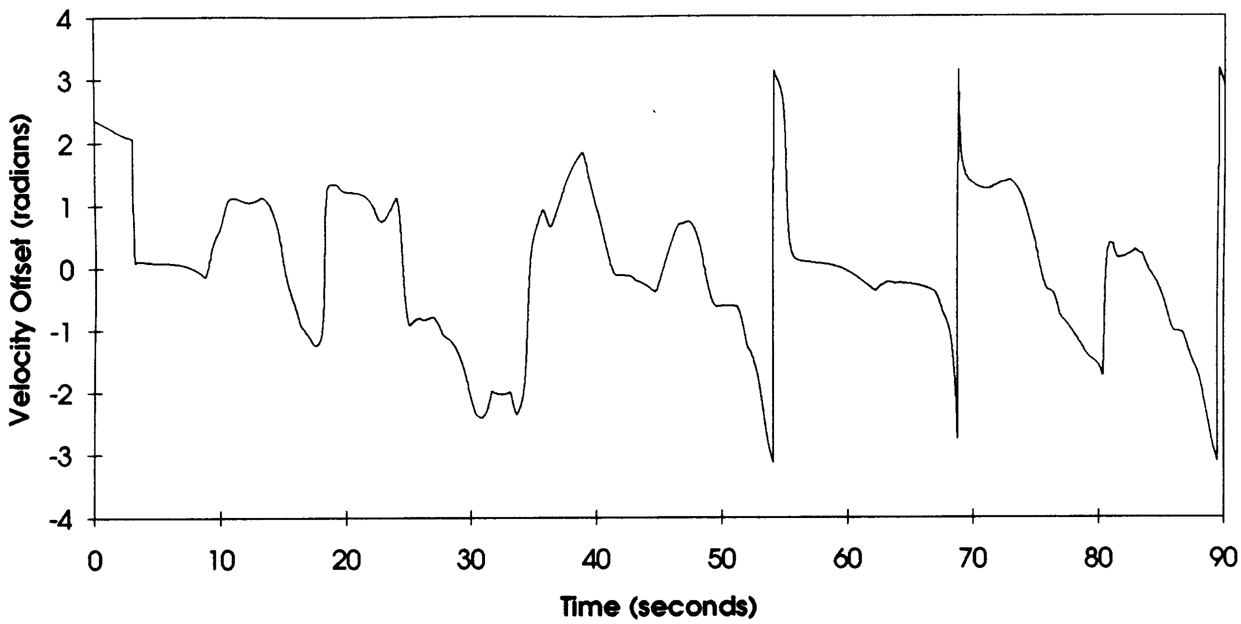

Figure 5-2: **Continuous Plot of Velocity Offset versus Time for a Run**

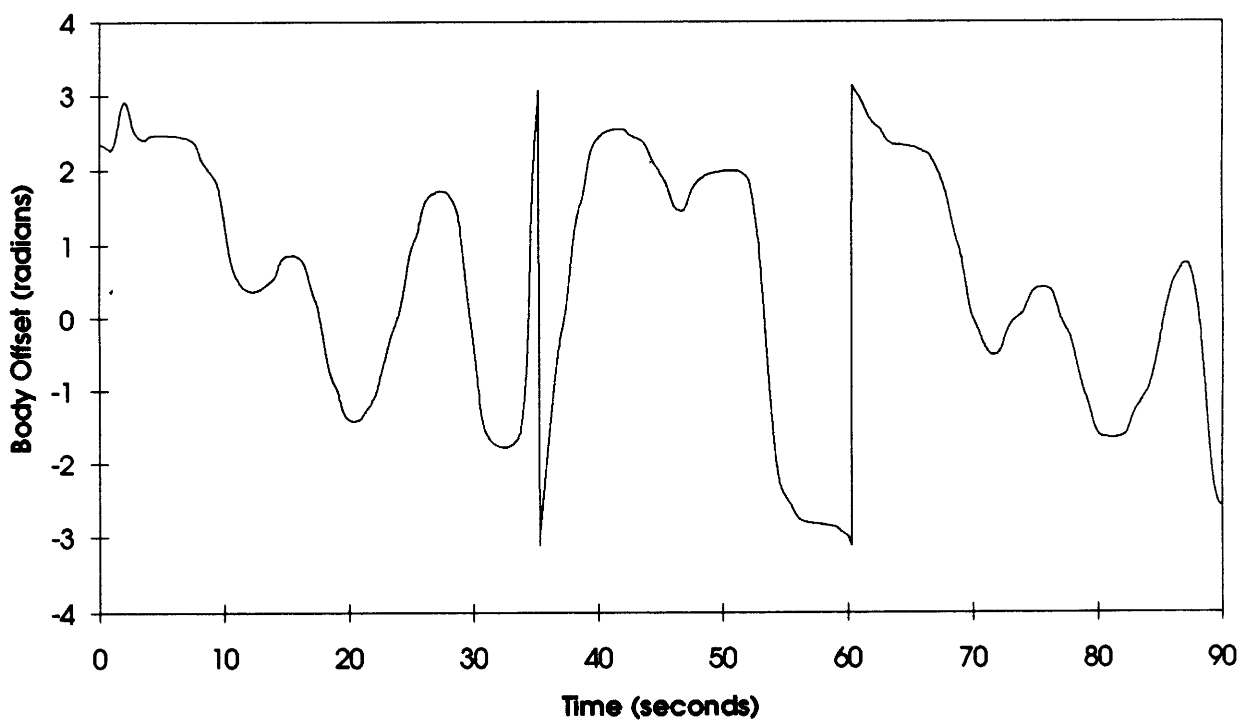

Figure 5-3: **Continuous Plot of Body Offset versus Time for a Run**

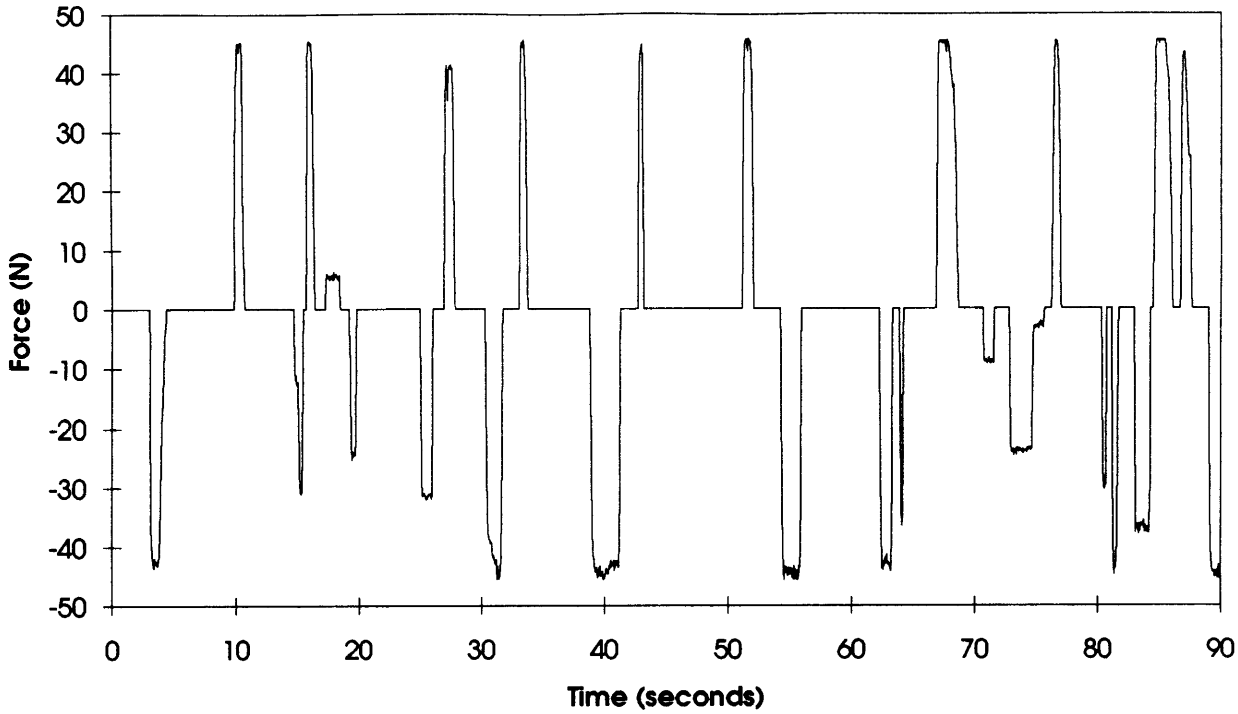

Figure 5-4: **Continuous Plot of Force (x) versus Time for a Run**

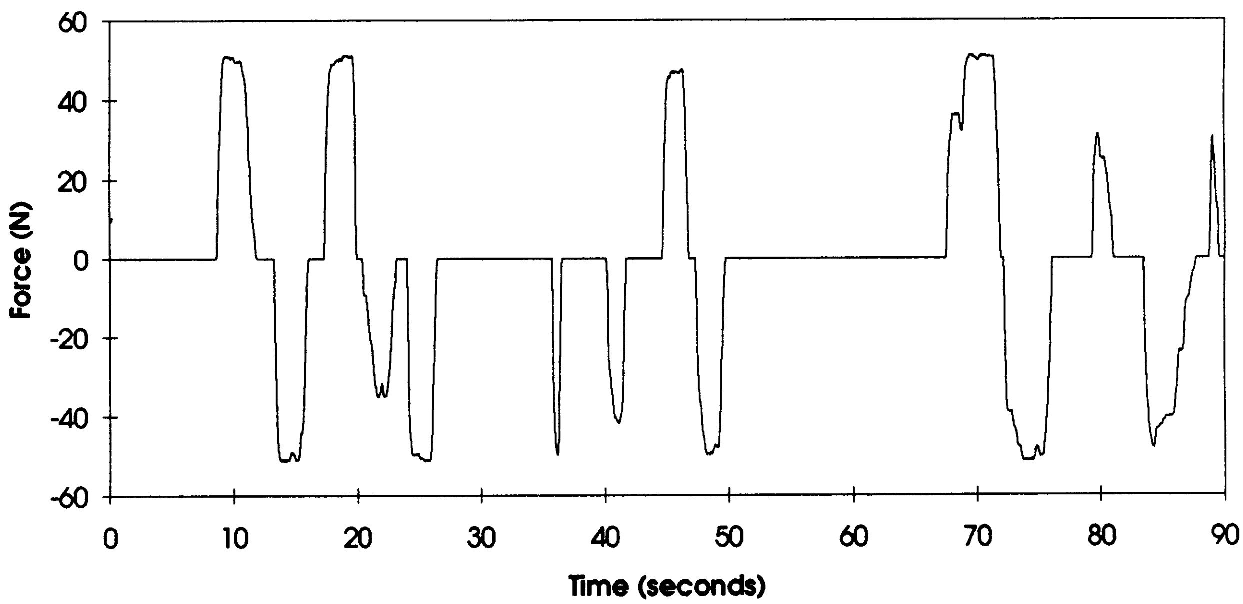

Figure 5-5: **Continuous Plot of Force (y) versus Time for a Run**

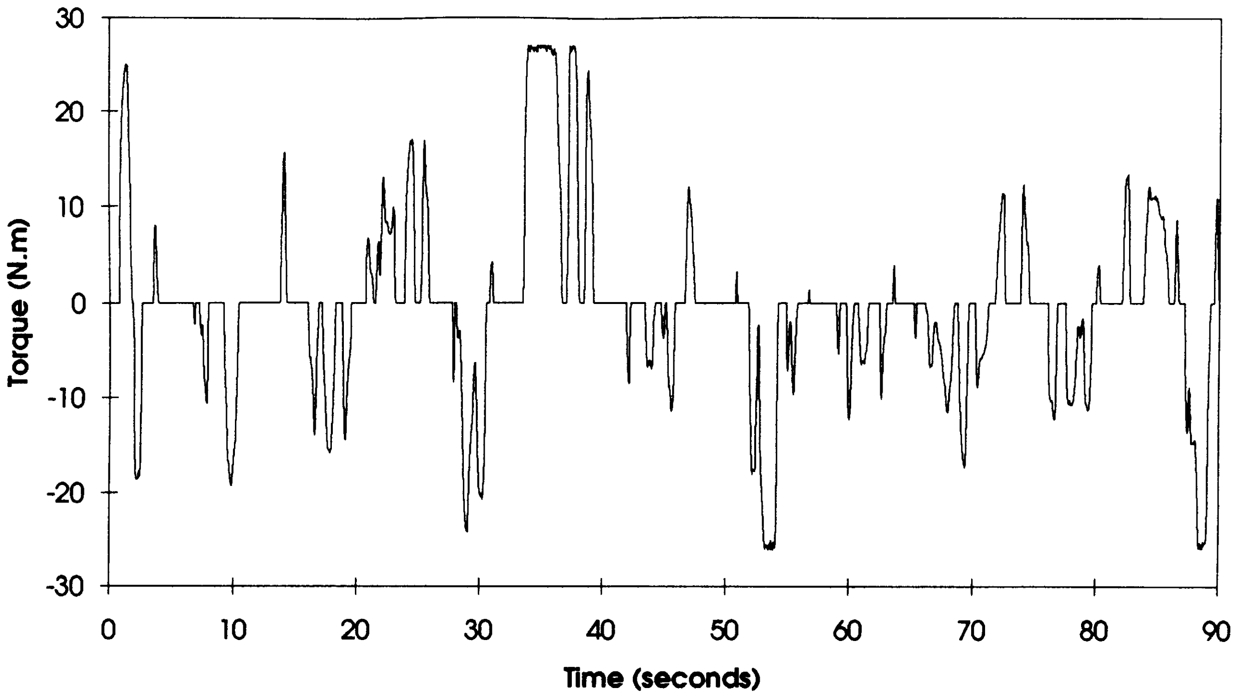

Figure 5-6: **Continuous Plot of Torque (yaw) versus Time for a Run**

5.3 Statistical Analysis

The matrix form of the data where each factor has a single value for each run allows a number of statistical techniques to be used. The primary advantage of the format is that each performance metric may be analyzed relative to each of the experimental parameters (the first ten factors of Figure 4-3). There are a number of methods for obtaining such descriptions and comparisons. The first method is to plot the values of performance metric versus each factor. These plots provide a strong indication as to the significance of the various factors and provide direction for numerical analysis. The initial numerical technique is to compute the summary statistical values for each metric over specific factors and also over a subset of each factor (such as over one of the values taken by the factor). The useful summary statistics are listed, with a label for reference.

- MIN - minimum value
- MAX - maximum value
- RANGE - difference of maximum and minimum values

- MEAN - mean or average value
- VAR - variance of the set of values
- STDEV - standard deviation of the set of values
- MED - median or middle value
- KUR - kurtosis
- SKEW - skew

These statistics are defined in [6]. Mean and median attempt to measure the center of the data distribution. Standard deviation and variance measure the spread. Kurtosis measures the peakedness, with a positive value indicating a longer tail than for a normal distribution. Skewness measures the symmetry of the distribution, with a positive value indicating a longer right tail.

The most useful technique for analysing data in matrix form is analysis of variance (ANOVA). The experiment and form of the data were specifically structured for this type of analysis. The variance $\hat{V}$ of a set of data is the mean square deviation (MS) of the measures from the grand mean (equation 5.1), and is equal to the sum of squares (SS) divided by the degrees of freedom (dof).

$$\hat{V} = \hat{\sigma}^2 = \frac{1}{N-1} \sum (x - \bar{x})^2 \tag{5.1}$$

When there are a number of factors or treatments which are varied to produce a set of data, it is useful to compute the variance between factors and within factors. The null hypothesis assumes that the data is drawn from a common population, and therefore, that the between sample variance is simply a subset of the variance of all the data. The assumption is that these two variances are independent estimates of the same population variance. Snedecor's variance ratio (F) tests the significance of the difference between treatment variances. An F ratio (larger divided by smaller variance) and the degrees of freedom involved yield a probability (p) value that the difference in variances is not significant. If the p value is small, the null hypothesis

source	SS	dof	MS	F	p
treatment ...					
error					

Figure 5-7: **Form of the ANOVA Table**

may be rejected. The general conclusion in this case is that the variance within or between treatments is not simply the variance expected from a common population or set of data. An external factor is typically postulated to explain this difference. The results of ANOVA are presented in a table, whose form is shown in Figure 5-7. The error accounts for the remainder of the population variance not attributed to the treatments listed.

The following sections present analysis of each of the performance metrics for each of the subjects and for the pooled data for all subjects.

5.4 Separation

Separation is a measure of the average distance between target and vehicle over a complete 90 second run. The initial analysis attempts to isolate two of the main factors which affect this performance metric. The first significant factor is the trajectory. Performance for each subject is strongly related to the fact that six quite different trajectories were used. The second significant factor is the learning effect. Subject performance is more variable over the first few of the six days of experimentation. The following graphs show each of these factors (Figures 5-8 to 5-13). The six plots show separation versus target trajectory for each of the three subjects. The first plot of each pair includes data for all days. The second shows results for all but the first two days.

These results lead to a number of observations and conclusions, some quite relevant to the form and validity of additional analysis. First, performance in tracking as measured by average separation depends significantly on the target trajectory. The proof is the difference between mean performance and between variance for each

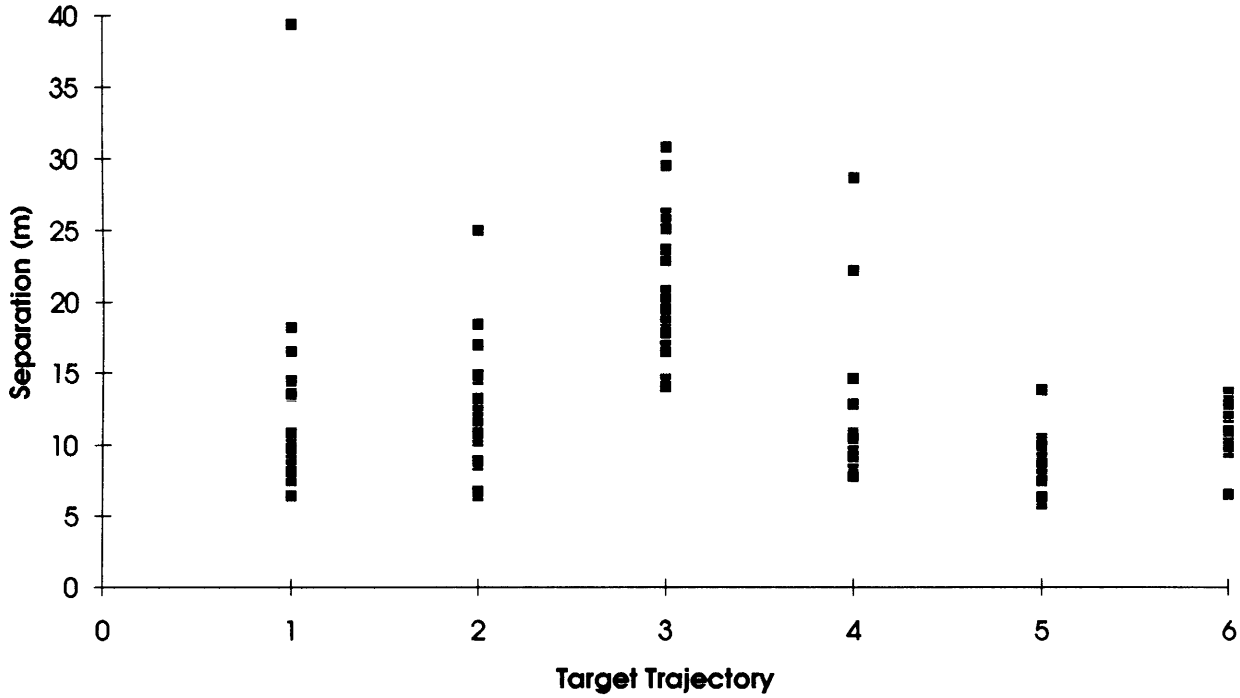

Figure 5-8: **Separation v Target Trajectory (subject 1, all days)**

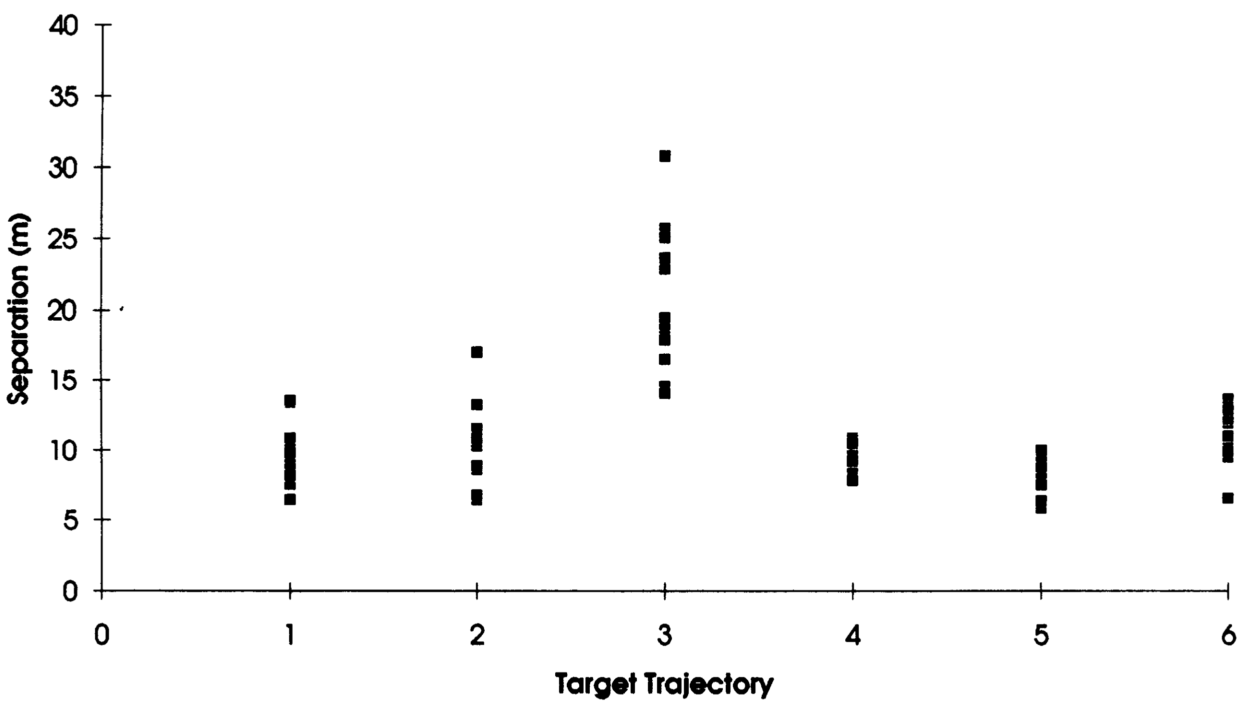

Figure 5-9: **Separation v Target Trajectory (subject 1, days 3-6)**

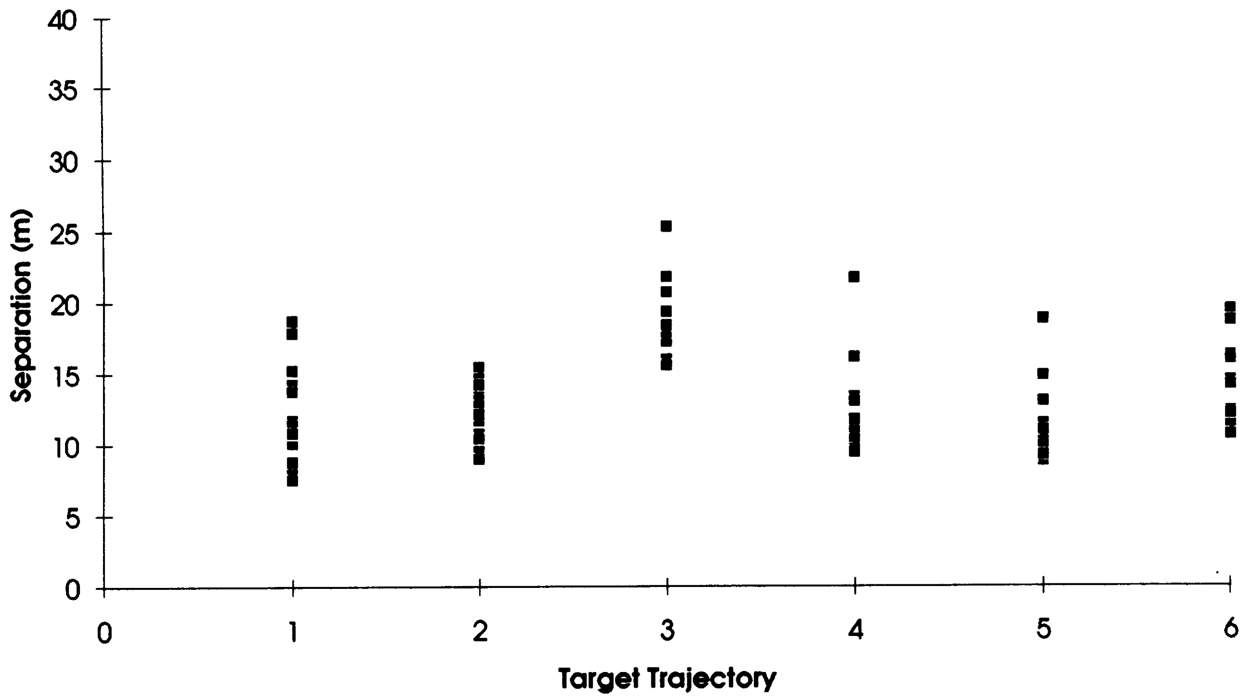

Figure 5-10: **Separation v Target Trajectory (subject 2, all days)**

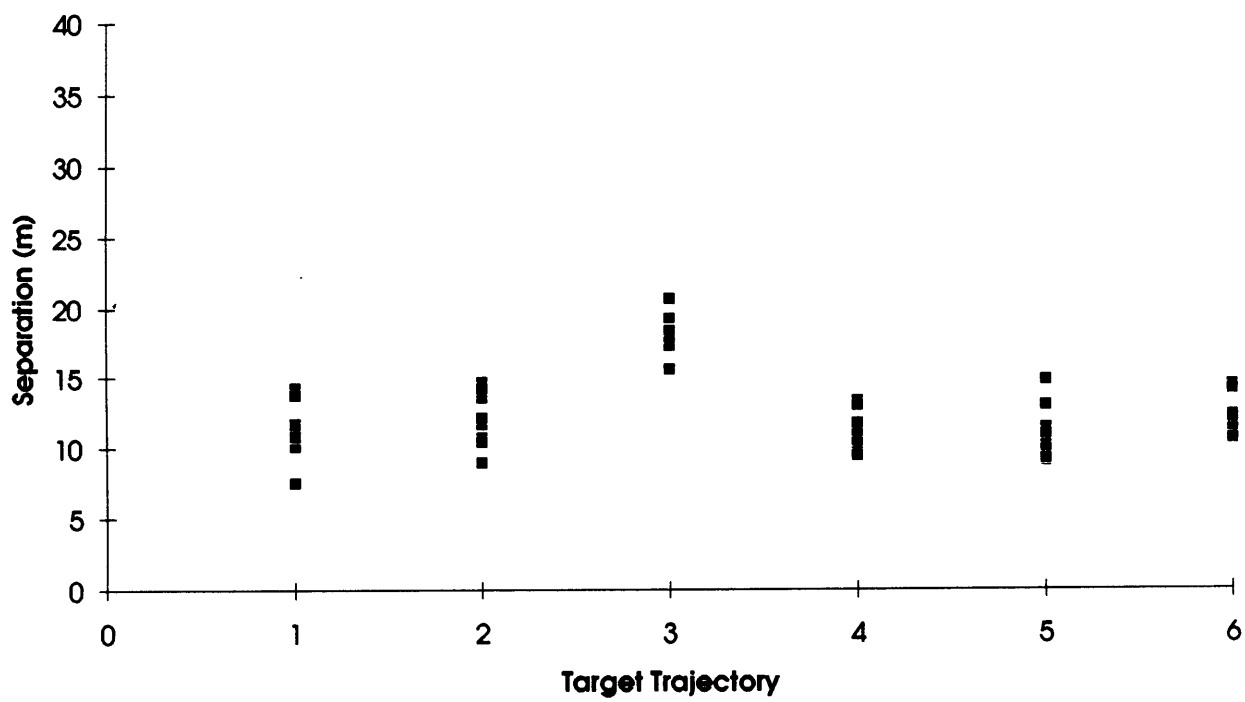

Figure 5-11: **Separation v Target Trajectory (subject 2, days 3-6)**

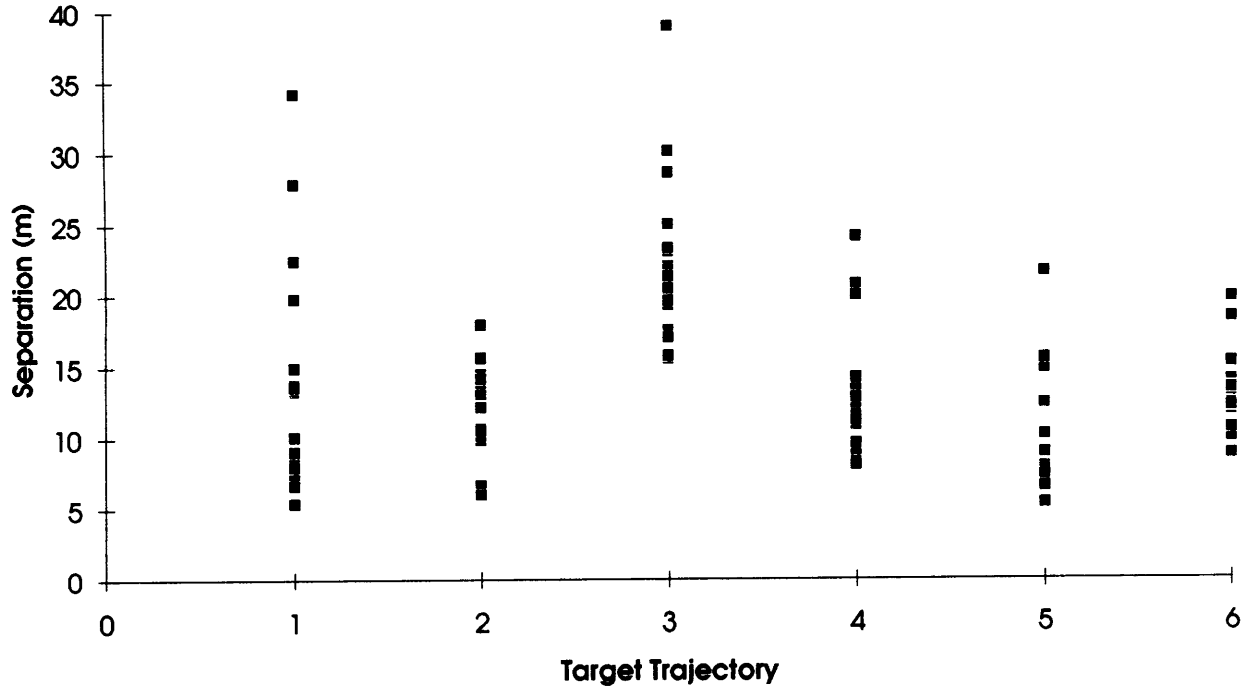

Figure 5-12: **Separation v Target Trajectory (subject 3, all days)**

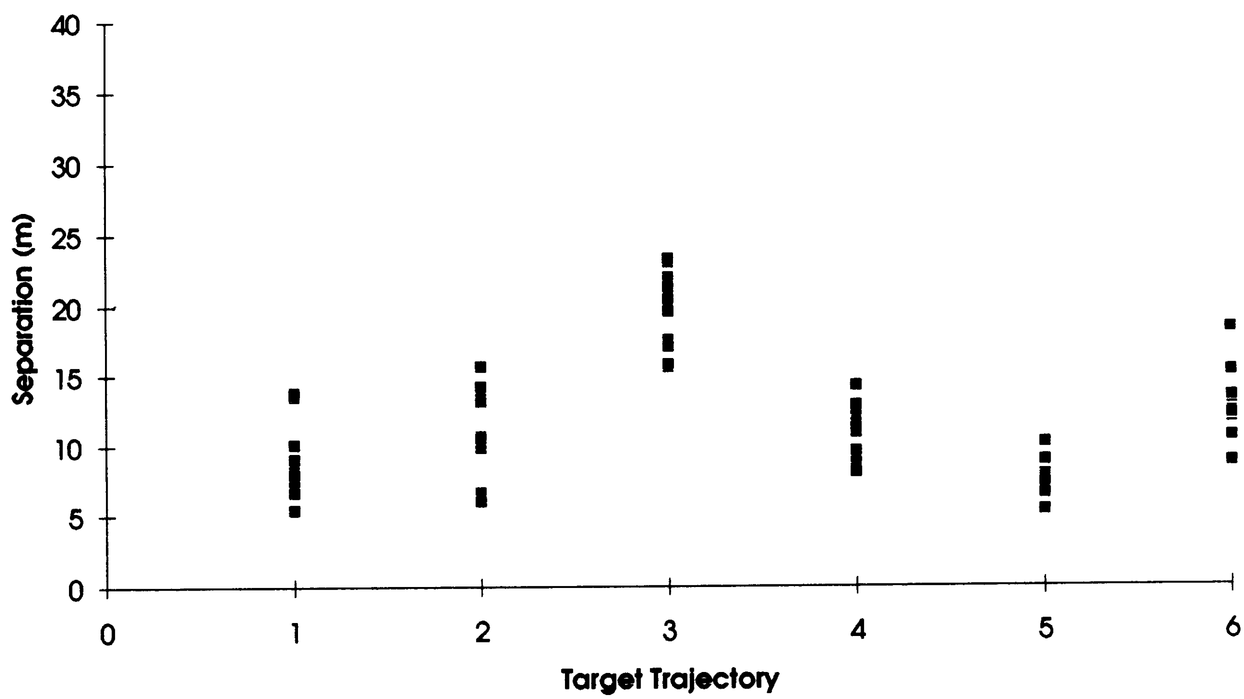

Figure 5-13: **Separation v Target Trajectory (subject 3, days 3-6)**

trajectory. Particularly when the first two days are removed, each trajectory has a distinctive mean separation with small variance about that mean. The order of difficulty (if it can be related to the separation) of the trajectories is quite similar for all subjects, with trajectory three resulting in the largest separation for all. Because the variance (range) of data for each trajectory are clearly clustered about their own mean, an ANOVA will show a strong dependency on the trajectory factor.

The second important observation from this data is that variance for each trajectory for each subject is nearly minimized by removing results from the first two days of testing. Removal of more than the first two days has neglible additional effect on the variance. The experiment design anticipates these first two days of learning and makes it easy to drop these results from the data pool. All results from this point on will involve only days three to six, unless noted. Analysis is much more successful when the major sources of variance are anticipated, observed and accounted for.

The third observation is that tracking performance as measured by separation is subject specific. While each subject had close to equal mean separation for each trajectory, the spread of the data about that mean differed between subjects. For example, subject three had one to two times more variance for each trajectory than subject two. What this means is that it is more useful to look at performance within subjects than between subjects. Pooling all data would include a systematic effect which results in this noticeable difference of variances.

The next consideration is whether or not to pool the data for all six trajectories for each subject. The table of summary statistics in Figure 5-14 shows the results for separation sorted by trajectory for each subject. The fact that individual trajectory variances are sigificantly smaller than the pooled variance for each subject indicates that trajectory is a significant factor in ANOVA. It seems valid to pool the trajectories for a subject since the trajectory variances are almost all less than half the size of pooled variances. The skew statistic is also interesting. Its value is positive for almost all trajectories for each subject. When separation for a run is greater than the mean value for that trajectory, it is typically further above the mean than are separations below the mean.

SUBJ	TRAJ	min	max	range	mean	var	skew	kurt
1	1	5.4	13.8	8.4	9.1	8.9	0.61	-1.15
	2	6.0	15.6	9.6	10.6	10.1	-0.62	-1.07
	3	15.6	23.3	7.7	19.9	7.6	-0.44	-1.28
	4	8.1	14.2	6.2	10.7	3.8	0.17	-1.08
	5	5.3	10.2	4.8	7.5	1.5	0.57	0.42
	6	8.8	18.3	9.6	12.9	5.5	0.63	1.02
	all	5.3	23.3	17.9	11.8	21.9	0.84	-0.06
2	1	6.4	13.5	7.1	9.5	4.8	0.79	-0.34
	2	6.4	16.9	10.5	10.1	9.1	0.72	0.22
	3	14.0	30.8	16.8	20.6	25.4	0.51	-0.60
	4	7.8	10.8	3.0	9.1	1.4	0.19	-1.60
	5	5.8	9.9	4.1	7.7	1.5	0.19	-0.72
	6	6.5	13.6	7.1	11.3	3.9	0.57	-1.10
	all	5.8	30.8	25.0	11.4	25.6	1.80	3.10
3	1	7.5	14.2	6.7	11.0	3.0	0.10	0.48
	2	9.0	14.6	5.7	12.2	3.6	-0.17	-1.30
	3	15.5	20.6	5.1	18.2	1.5	-0.26	0.76
	4	9.4	13.3	3.9	11.0	1.7	0.53	-0.88
	5	9.0	14.8	5.7	10.7	2.9	1.20	0.81
	6	10.6	14.4	3.8	12.1	1.3	1.00	0.32
	all	7.5	20.6	13.1	12.5	9	1.00	0.11

Figure 5-14: **Separation Statisitics for Trajectories**

source	SS	dof	MS	F	p
TRAJ	1008.9	5	201.8	30.1	2E-12
DAY	125.9	3	42	6.25	0.0014
error	261.7	39	6.71		

source	SS	dof	MS	F	p
TRAJ	326.1	5	65.2	12.1	8E-05
DAY	5.88	3	1.96	0.362	0.781
error	81.2	15	5.41		

Figure 5-15: **Separation ANOVA for hmd and monitor (subject 1)**

	Mean Separation	
Day	monitor	hmd
3	11.7	13.9
4	10.5	12.3
5	11	10.5
6	10.5	9.7

Figure 5-16: **Separation Mean Values (subject 1)**

ANOVA performed on separation for subject one shows only trajectory and day to be significant factors. Figure 5-15 shows the results for ANOVA taken for runs with only the head mounted display (top) and with only the monitor display (bottom). With the monitor display, as opposed to the head mounted display, the factor of day is not significant. What do these results imply? The significance of trajectory is simply the result already discussed, with the mean values shown in Figure 5-14. The significance of day implies that there is a continued learning effect after day two with the hmd. The table in Figure 5-16 lists the mean separation values for each day for each display. While the monitor shows no pattern, hmd shows a declining trend which was found significant by ANOVA. None of the other factors appear significant.

Subject two has the smallest variance for separation versus trajectory over each trajectory as well as the smallest range of variances over all trajectories (Figure 5-14). This implies that, while the mean separations (performance) vary with trajectory, the subject shows more consistent performance over each trajectory than the other

source	SS	dof	MS	F	p
TRAJ	486.6	5	97.3	55.7	1E-15
BODY	39.5	1	39.5	22.6	1E-05
error	113.5	65	1.75		

source	SS	dof	MS	F	p
TRAJ	320.4	5	64.1	48	1E-15
BODY	23	1	23	17.2	2E-04
BODY*TRACK	4.21	1	4.21	3.15	0.084
error	53.4	40	1.34		

Figure 5-17: **Separation ANOVA for all cases and hmd (subject 2)**

subjects. Analysis within each trajectory of the other experimental factors would be most succesful in this situation but there are too few measurements for each factor to provide valid comparisons. Hence, all trajectories are pooled for analysis.

ANOVA for subject two indicates that there are two significant factors (Figure 5-17), trajectory and body representation. Taking only the cases when the hmd is used, an additional cross effect of body and head tracking is somewhat significant (head tracking is not used in conjunction with the monitor display). The table in Figure 5-18 indicates the mean separation values for the various cases when the hmd is used. Although the head tracking effect is unclear, the addition of the body representation results in larger separation values. This is also true for the monitor case and for every trajectory. One possible conclusion is that, for this subject, the addition of the body representation is simply an overlay which acts like the frame of the monitor. While the subject trys to keep a stable distance from the target, they use the monitor frame as a reference. That is, the size of the target relative to the screen size is the cue which indicates its distance away. When the body representation is added, it effectively reduces the screen size, acting as the viewing frame. To keep the full target within view, or the same relative target size, the separation must be larger.

The third subject also demonstrates significance of the trajectory and body representation factors (Figure 5-19). For five of the six trajectories, in both the hmd and monitor cases, the subject has a larger mean separation with the body representation

BODY	TRACK	Separation
1	1	12.3
1	2	11.7
2	1	13.1
2	2	13.7

Figure 5-18: **Separation Mean Values for hmd (subject 2)**

source	SS	dof	MS	F	p
TRAJ	1142.8	5	228.6	38.7	1E-15
BODY	28.3	1	28.3	4.78	0.0323
error	384.3	65	5.91		

Figure 5-19: **Separation ANOVA (subject 3)**

than without. Only the case of the fourth trajectory shows the opposite. The probability that this result is random is less than ten percent $(6(\frac{1}{6})^2)$. It appears that this subject also adopts the strategy of maintaining an observable target size relative to the monitor or body frame (screen size).

Data for all three subjects is also pooled for addditional examination of trajectory separation. The ANOVA of Figure 5-20 shows the significant factors. The fact that subject is significant indicates the performance difference between subjects. The cross effect of subject and trajectory indicates that this performance difference exists for each trajectory as well. The tables of Figure 5-21 list the mean separation values for the significant cases. The pooled data indicates that there is a steady decrease in separation by day even with the removal of the first two days, indicating continued learning or improved tracking. The addition of the body representation significantly increases mean separation. The hmd results in slightly larger mean separation than the monitor display. While prime was found somewhat significant, the nearly equal mean values indicate that the use of mirror image trajectories causes no systematic performance differences overall, as expected.

source	SS	dof	MS	F	p
DAY	65.2	3	21.7	4.58	0.004
TRAJ	2779.3	5	555.9	117.2	1E-15
SUBJ	49.7	2	24.8	5.24	0.006
TRAJ*SUBJ	159	10	15.9	3.35	0.005
BODY	45.3	1	45.3	9.55	0.002
MON	13.2	1	13.2	2.79	0.096
PRIME	19.7	1	19.7	4.16	0.043
error	910.9	192	4.74		

Figure 5-20: **Separation ANOVA (all subjects)**

DAY	Separation
3	12.76
4	12.11
5	11.74
6	11.04

SUBJ	Separation
1	11.39
2	12.55
3	11.80

BODY	Separation
1	11.29
2	12.35

MON	Separation
1	11.56
2	12.09

PRIME	Separation
1	11.90
2	11.75

Figure 5-21: **Separation Mean Values (all subjects)**

source	SS	dof	MS	F	p
SLOT	0.1990	2	0.0995	7.0200	0.0018
BODY	0.1249	1	0.1249	8.8200	0.0042
TRAJ	0.5190	5	0.1038	7.3300	1.8E-05
error	0.8922	63	0.0142		

Figure 5-22: **Velocity Offset ANOVA (subject 1)**

5.5 Velocity Offset

As discused in section 4.2, velocity offset is the angular difference (in radians) between the direction of motion and the direction of the target relative to the vehicle. This metric is expected to relate back to the second tracking goal: be moving towards the target. A velocity offset of zero indicates best tracking performance. The average rms value of velocity offset for a run is expected to demonstrate how close to perfect angular tracking is achieved. The limitations of this metric were discussed in section 4.1. Its value as a performance metric can only be derived by analyzing and interpreting the results.

ANOVA of velocity offset for the first subject (Figure 5-22) lists three significant factors: slot (there are three slots of six runs in a day), body representation and trajectory. The effect of body will be discussed with the pooled data for all subjects. The table (Figure 5-23) of mean values for the three slots indicates an increasing trend. Either the subject is sacrificing more angular tracking performance in later runs on a day or this result is not particularly relevant. The effect of slot was not found to be significant for all other performance metrics for this subject and other subjects. The trajectory effect is found significant for this and other subjects. Reasons for this, discussed in depth for other metrics, can be extrapolated to this metric as well.

Subject number two shows significant effects of day and trajectory, while body representation was found not significant (Figure 5-24). Mean values by day (Figure 5-25) demonstrate a somewhat declining trend, possibly indicating a learning effect. The third subject demonstrates a similar day effect, with the addition of a monitor effect (Figures 5-26 and 5-27). The hmd appears to result in a lower value of velocity

SLOT	VTR
1	0.948
2	1.037
3	1.077

Figure 5-23: **Velocity Offset Mean Values by Slot (subject 1)**

source	SS	dof	MS	F	p
DAY	0.3920	3	0.1307	4.9590	0.0038
BODY	0.2108	5	0.0422	1.6000	0.1734
TRAJ	0.0971	1	0.0971	3.6840	0.0595
error	1.6337	62	0.0263		

Figure 5-24: **Velocity Offset ANOVA (subject 2)**

offset, possibly indicating improved tracking.

While the individual results for velocity offset offer few decisive conclusions, the pooled results show a little more significance. The ANOVA (Figure 5-28) shows the significance of subject with numerous cross effects. Subjects perform differently (Figure 5-30) and also seem to adopt differing strategies. The monitor effect observed for subject three is thus likely significant. One recurring factor is the body representation: all subjects demonstrate better performance without it (Figure 5-29). As discussed in the previous section, the body representation results in increased separation. It also seems reasonable that at larger distances, angular tracking will be less accurate. Because the image of the target appears smaller in size, it is easier to keep it completely within view over a larger angular range or field of view.

DAY	VTR
3	1.078
4	0.972
5	0.877
6	0.916

Figure 5-25: **Velocity Offset Mean Values by Day (subject 2)**

source	SS	dof	MS	F	p
DAY	0.1485	3	0.0495	2.6620	0.0558
MON	0.1110	1	0.1110	5.9690	0.0174
TRAJ	0.3834	5	0.0767	4.1230	0.0027
error	1.1532	62	0.0186		

Figure 5-26: **Velocity Offset ANOVA (subject 3)**

DAY	VTR
3	1.217
4	1.120
5	1.108
6	1.186

MON	VTR
1	1.213
2	1.130

Figure 5-27: **Velocity Offset Mean Values (subject 3)**

source	SS	dof	MS	F	p
SUBJ	0.357	2	0.179	9.22	0.0002
DAY	0.209	3	0.086	4.47	0.0047
TRAJ	0.353	5	0.071	3.65	0.0036
BODY	0.147	1	0.147	7.60	0.0065
TRAJ*PRIME	0.222	5	0.045	2.30	0.0471
SUBJ*TRAJ	0.451	10	0.045	2.33	0.0132
SUBJ*MON	0.127	2	0.063	3.27	0.0404
SUBJ*PRIME	0.148	2	0.073	3.76	0.0249
SUBJ*DAY	0.269	6	0.045	2.31	0.0355
error	3.465	179	0.019		

Figure 5-28: **Velocity Offset ANOVA (all subjects)**

	SUBJ			
BODY	1	2	3	all
1	0.9760	0.9210	1.1470	1.0230
2	1.0650	0.9990	1.1670	1.0720

Figure 5-29: **Velocity Offset Mean Values by Body (all subjects)**

DAY	VTR
3	1.093
4	1.055
5	0.996
6	1.038

SUBJ	VTR
1	1.018
2	0.961
3	1.158

BODY	VTR
1	1.023
2	1.072

Figure 5-30: **Velocity Offset Mean Values (all subjects)**

DAY	CDT
3	40.75
4	38.08
5	41.45
6	43.00

MON	TRACK	CDT
1	1	42.00
2	1	38.32
2	2	43.46

Figure 5-31: **Change of Direction Mean Values (subject 1)**

5.6 Change in Direction

A change in direction is defined as a change in sign of the first derivative of θ_{vt} over time. The value represents the number of these changes over a run. It is specifically computed by looking at a continuous time plot of θ_{vt} versus time for each run. An examination of mean values and ANOVA for the experimental factors is necessary to determine any trends or significance in this data.

Figure 5-31 shows mean values of change in direction for subject one for a number of cases. Figure 5-32 is the ANOVA table for this subject. A number of significant factors do appear. Day is significant, although the pattern is unclear. A cross effect of monitor and track appears significant. The number of changes of direction is smallest for the hmd without head tracking and largest with head tracking. The significance of trajectory, body representation and head tracking are discussed with the pooled results for all subjects.

The second subject also demonstrates a dependence on trajectory, as well as body representation, and head tracking with a cross effect (Figure 5-33). This effect is examined more closely in Figure 5-34. The addition of the body representation results

source	SS	dof	MS	F	p
TRAJ	704.6	5	140.2	4.128	0.0027
DAY	328.5	3	109.5	3.208	0.0293
MON*TRACK	161.3	1	161.3	4.726	0.0337
BODY	291.8	1	291.8	8.550	0.0049
TRACK	266.1	1	266.1	7.795	0.0070
error	2048.1	60	34.1		

Figure 5-32: **Change of Direction ANOVA (subject 1)**

source	SS	dof	MS	F	p
TRAJ	542.4	5	108.5	6.320	9.5E-05
BODY	463.3	1	463.3	27.010	2.7E-06
TRACK	141.0	1	141.0	8.220	0.0058
BODY*TRACK	184.9	1	184.9	10.780	0.0017
TRAJ*PRIME	310.7	5	62.2	3.620	0.0064
error	994.9	58	17.2		

Figure 5-33: **Change of Direction ANOVA (subject 2)**

in fewer direction changes, particularly when head tracking is not used. The cross effect of trajectory and mirror imaging (prime) is an important effect. What this indicates is that, for a particular trajectory, performance is different for its mirror image. This leads to the inference of a directional bias in the tracking strategy.

ANOVA for the third subject (Figure 5-35) indicates that trajectory and day are likewise significant, along with cross effects of trajectory, day and body representation. What the cross effect of trajectory and day indicates is that while performance varies

DAY	CDT
3	39.27
4	35.79
5	40.21
6	38.29

BODY	TRACK	CDT
1	1	41.92
1	2	41.33
2	1	33.13
2	2	38.92

Figure 5-34: **Change of Direction Mean Values (subject 2)**

source	SS	dof	MS	F	p
TRAJ	1320.2	5	264.0	9.480	8.8E-06
BODY	86.7	1	86.7	3.110	0.086
TRAJ*DAY	823.1	15	54.9	1.970	0.049
TRAJ*BODY*DAY	717.2	15	47.8	1.720	0.093
error	974.6	35	27.9		

Figure 5-35: **Change of Direction ANOVA (subject 3)**

with trajectory, it also depends upon the day in which the trajectory appears. The cross effect of trajectory, body and day draws upon single data points and thus provides little inference.

The pooled data of change of direction for all subjects yields interesting results. An ANOVA (Figure 5-36) indicates that subject, day, trajectory, body, head tracking and a cross effect are significant. The ensuing tables (5-37 to 5-40) list the performance means for a number of factors. Overall, subject two has the fewest direction changes per run. All subjects have fewer direction changes when the body representation is used. All subjects also show more direction changes when head tracking is used. It seems reasonable that head tracking result in more direction changes. As subjects move their direction of view from side to side, it is possible that they confuse this with a change in orientation of the vehicle. This perception may lead to an orientation correction through a torque command. This correction shows up in this metric, change of direction.

The order of performance over the six trajectories are quite similar between subjects. Trajectory five generally results in the most direction changes while trajectory three has the least. A very interesting correlation exists with tracking performance as measured by average separation from the target. Figure 5-14 indicates that trajectory five results in the lowest separation values while trajectory three results in the largest. A possible conclusion is that when subjects are able to track closer to the target, they also make more corrections in their direction of motion relative to the target. There is a physical justification for this behaviour. When the target is

source	SS	dof	MS	F	p
SUBJ	305.6	2	152.8	4.970	0.0079
DAY	466.4	3	155.5	5.060	0.0022
TRAJ	2290.6	5	458.1	14.900	2.6E-12
DAY*TRAJ	777.8	15	51.9	1.690	0.0564
BODY	1213.4	1	1213.4	39.480	2.3E-09
TRACK	171.3	1	171.3	5.570	0.0193
error	5778.6	188	30.7		

Figure 5-36: **Change of Direction ANOVA (all subjects)**

SUBJ	CDT
1	41.26
2	38.39
3	40.24

Figure 5-37: **Change of Direction Mean Values by Subject (all subjects)**

moving from side to side at some velocity, when an operator is closer to the target, it will appear to move more rapidly across the field of view. Consequently, the operator may make more direction adjustments or corrections in order to keep the target centered within their field of view. This relates back to the body representation, whose addition resulted in larger separations, and so, by this arguement, in fewer direction changes (Figure 5-38).

	SUBJ			
BODY	1	2	3	all
1	42.96	41.63	41.33	42.26
2	38.69	36.02	39.14	38.29

Figure 5-38: **Change of Direction Mean Values by Body (all subjects)**

TRACK	SUBJ 1	2	3	all
1	40.17	37.52	40.31	39.33
2	43.46	40.13	40.08	41.22

Figure 5-39: **Change of Direction Mean Values by Head Tracking (all)**

TRAJ	SUBJ 1	2	3	all
1	40.88	36.17	35.63	37.97
2	39.38	35.17	37.26	37.64
3	35.38	35.83	34.76	35.22
4	44.50	42.00	43.82	43.14
5	45.06	41.17	46.69	44.39
6	39.35	40.00	43.26	41.42

Figure 5-40: **Change of Direction Mean Values by Trajectory (all subjects)**

5.7 Head Orientation

Head orientation angle is a measure of the direction of view of the operator relative to the body frame when head tracking is used. A value of zero means that the operator is looking straight ahead and a positive value occurs when looking left. As indicated in section 4.2, both average and rms average values are computed for each run. Figure 5-41 lists statistics for head orientation in the case of head tracking and for velocity and body offset for all cases. Average head orientation (HT) demonstrates whether there is a directional bias. If the mean value is positive and the standard deviation is small relative to the mean, then the subject has a tendency to look more often or further in the left direction. Subject two is the only one to demonstrate this tendency. Skew also indicates a tendency to rotate further in one direction. Positive skew means that the subject tends to rotate further in the left direction. The mean value of rms average head orientation (HTR) indicates the amount of head rotation used; a large value indicates that the subject turns their head more often or rotates further.

SUBJ	FACTOR	min	max	range	mean	var	skew	kur	med	stdev
1	HT	-0.136	0.154	0.290	0.016	0.004	0.196	1.593	0.010	0.059
	HTR	0.037	0.160	0.123	0.086	0.002	0.416	-1.172	0.079	0.041
	BT	-0.628	0.616	1.245	-0.006	0.087	0.187	-0.782	-0.061	0.295
	BTR	1.107	2.154	1.047	1.612	0.054	0.100	-0.176	1.605	0.233
	VT	-0.530	0.722	1.252	0.190	0.080	-0.318	-0.434	0.197	0.282
	VTR	0.649	1.310	0.661	1.018	0.023	-0.028	-0.539	1.021	0.152
2	HT	-0.067	0.167	0.233	0.064	0.004	-0.430	-0.328	0.067	0.063
	HTR	0.030	0.186	0.155	0.105	0.002	0.359	-0.838	0.099	0.043
	BT	-0.894	1.144	2.038	0.083	0.161	0.199	-0.019	0.075	0.401
	BTR	1.235	2.026	0.792	1.553	0.032	0.130	-0.546	1.549	0.180
	VT	-0.568	0.788	1.357	0.090	0.067	0.123	-0.173	0.075	0.258
	VTR	0.592	1.526	0.935	0.961	0.033	0.282	0.405	0.966	0.182
3	HT	-0.188	0.204	0.392	0.004	0.010	-0.156	-0.416	0.022	0.097
	HTR	0.049	0.238	0.189	0.123	0.003	0.738	-0.523	0.109	0.055
	BT	-1.291	1.155	2.446	0.066	0.237	-0.391	0.055	0.127	0.487
	BTR	0.987	1.987	1.000	1.531	0.047	-0.162	-0.059	1.543	0.216
	VT	-0.669	0.817	1.487	0.047	0.089	0.011	0.096	0.054	0.298
	VTR	0.750	1.594	0.844	1.158	0.025	0.293	0.268	1.151	0.159

Figure 5-41: **Head Orientation, Velocity and Body Offset Stats**

source	SS	dof	MS	F	p
DAY	0.0211	3	0.0070	7.683	0.0013
error	0.0183	20	0.0009		

source	SS	dof	MS	F	p
BODY	0.0188	1	0.0188	20.010	0.0002
error	0.0206	22	0.0009		

source	SS	dof	MS	F	p
BODY	247.0	1	247.0	4.690	0.0415
error	1158.9	22	52.7		

Figure 5-42: **Head Orientation ANOVA (subject 1)**

ANOVA for subject one indicate the relevance of various factors to head orientation (Figure 5-42). The first ANOVA demonstrates significance of day to rms head orientation. Interestingly, the significance of body is not present unless day is removed as a factor, as shown by the second table of that figure. The explanation is quite simple: on days three and five, body representation was used with head tracking and was not used on days four and six. Only one set of six runs were performed with head tracking on each day, hence the effects of day and body are confounded. Tables in Figure 5-43 indicate the results. Body representation results in significantly less use of head tracking. The third ANOVA of Figure 5-42 is of change of direction when head tracking is used. This result and the accompanying Figure 5-43 indicate that fewer direction changes are made with the body representation and head tracking by this subject. It seems that the added body reduces the number of direction changes and the amount of head tracking used. Subject three also demonstrates this body effect (Figures 5-44 and 5-45). The tendency for subject two to favour the left direction is demonstrated by the distribution plot of average head orientation, overlayed by the normal distribution (Figure 5-46).

DAY	HTR
3	0.0679
4	0.1232
5	0.0476
6	0.1042

BODY	HTR	CDT
1	0.1137	46.67
2	0.0578	40.25

Figure 5-43: **Head Orientation Mean Values (subject 1)**

source	SS	dof	MS	F	p
BODY	0.0093	1	0.0093	3.358	0.0804
error	0.0608	22	0.0028		

Figure 5-44: **Head Orientation ANOVA (subject 3)**

DAY	HTR
3	0.1324
4	0.1333
5	0.0739
6	0.1517

BODY	HTR
1	0.1125
2	0.1032

Figure 5-45: **Head Orientation Mean Values (subject 3)**

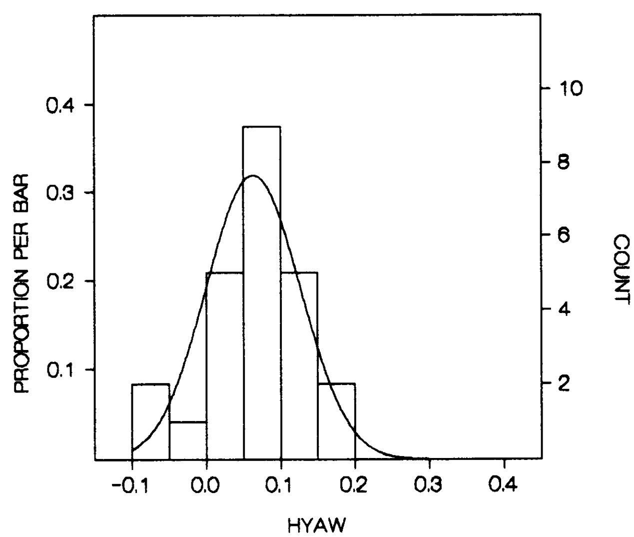

Figure 5-46: **Head Orientation Distribution (subject 2)**

SUBJ	FACTOR	min	max	range	mean	var	skew	kur	med	stdev
1	FX	-32.62	1.02	33.64	-9.88	26.07	-1.195	4.190	-9.35	5.11
	FY	-8.93	13.36	22.29	2.32	36.71	-0.069	-0.916	2.14	6.06
	TZ	-5.90	6.43	12.33	0.83	6.15	-0.108	-0.135	0.71	2.48
2	FX	-23.21	1.53	24.74	-8.95	29.97	-0.193	-0.579	-8.90	5.47
	FY	-10.90	19.24	30.13	1.43	37.53	0.341	0.015	1.60	6.13
	TZ	-6.55	4.45	11.00	-0.26	4.57	-0.262	0.486	-0.41	2.14
3	FX	-14.89	1.52	16.40	-3.33	6.98	-1.379	3.870	-2.78	2.64
	FY	-8.13	8.51	16.64	0.25	14.16	-0.185	-0.460	0.40	3.76
	TZ	-3.83	5.25	9.08	-0.10	2.40	0.343	1.106	0.02	1.55

Figure 5-47: **Average Force Command Statistics**

5.8 Force and Torque Commands

Metrics for force and torque are similar to head orientation in that both average and rms average values are interseting. Average values indicate directional bias while rms average indicates the total amount of force or torque commanded. The amount of force or torque used relates to tracking strategy. Forces are required to maintain proximity to the moving target while torque is required to keep the target within view. The statistics table for average forces and torque demonstrates the directional bias for each component (Figure 5-47). The mean values of force in the x direction are all negative. This indicates that operators tend to push forward on the x joystick rather than pull back. The y forces for all subjects are within a standard deviation of zero, indicating that subjects do not favour pushing towards the right or left directions (with the left hand). Torque mean values show a balanced use of clockwise and counter-clockwise commands.

Rms average force commands are analyzed to observe whether the amount of force and torque commanded in a run is significant. For subject one, ANOVA indicates that day and trajectory are significant for both force directions (Figures 5-48 and 5-49). TNUM is the position of the run within a slot, but shows no clear pattern. Monitor and body were found significant for y force only. The mean values are compared in Figure 5-50. The hmd increases the amount of y force used while the

source	SS	dof	MS	F	p
DAY	278.09	3	92.70	13.49	7E-07
TRAJ	409.00	5	81.80	11.91	4E-08
TNUM	143.52	5	28.70	2.74	0.0269
error	361.67	58	6.23		

Figure 5-48: **Rms Force (x) Command ANOVA (subject 1)**

source	SS	dof	MS	F	p
DAY	742.87	3	247.62	25.66	7E-11
TRAJ	227.63	5	45.53	4.72	0.0010
MON	135.31	1	135.31	14.02	0.0004
BODY	431.28	1	432.28	44.70	8E-09
error	588.61	61	9.65		

Figure 5-49: **Rms Force (y) Command ANOVA (subject 1)**

body representation reduces it.

ANOVA for subject two (Figures 5-51 and 5-52) indicate a significant body effect in both directions as well as a track effect in the x direction. Like subject one, there are no significant factors in torque commands. Mean values for this subject (Figure 5-53) demonstrates that head tracking decreases both translational force commands while body increases both. The body effect is opposite that of the previous subject.

Results for subject three (Figures 5-54 to 5-57) demonstrate few significant factors beyond the typical day and trajectory factors. There are slight track and body effects, but the pattern is unclear.

Rms force mean values for all subjects demonstrate the day and trajectory effects discovered (Figures 5-58 and 5-59). There is large variability among the trends by

MON	FXR	FYR
1	25.59	20.90
2	25.02	23.80

BODY	FXR	FYR
1	25.98	25.76
2	24.64	18.94

Figure 5-50: **Rms Force Mean Values (subject 1)**

source	SS	dof	MS	F	p
DAY	303.73	3	60.75	8.59	3E-06
TRAJ	327.23	5	109.08	15.42	1E-07
BODY	32.75	1	32.75	4.63	0.0354
TRACK	117.52	1	117.52	16.62	0.0001
error	431.45	61	7.07		

Figure 5-51: **Rms Force (x) Command ANOVA (subject 2)**

source	SS	dof	MS	F	p
DAY	419.87	3	139.96	14.33	3E-07
TRAJ	744.49	5	148.90	15.25	9E-10
BODY	38.12	1	38.12	3.90	0.0526
error	605.42	62	9.76		

Figure 5-52: **Rms Force (y) Command ANOVA (subject 2)**

TRACK	FXR	FYR
1	12.87	12.85
2	10.16	11.66

BODY	FXR	FYR
1	11.06	11.53
2	11.97	12.98

Figure 5-53: **Rms Force Mean Values (subject 2)**

source	SS	dof	MS	F	p
TRAJ	261.18	5	52.24	4.73	0.0010
MON	78.03	1	78.03	7.07	0.0099
TRACK	27.87	1	27.87	2.53	0.1169
error	706.21	64	11.03		

Figure 5-54: **Rms Force (x) Command ANOVA (subject 3)**

source	SS	dof	MS	F	p
DAY	229.66	3	76.55	4.46	0.0068
TRAJ	481.95	5	96.39	5.62	0.0003
BODY	57.90	1	57.90	3.37	0.0712
TRACK	55.74	1	55.74	3.25	0.0765
error	1047.16	61	17.17		

Figure 5-55: **Rms Force (y) Command ANOVA (subject 3)**

source	SS	dof	MS	F	p
DAY	47.61	3	15.87	5.73	0.0016
TRAJ	30.10	5	6.02	2.17	0.0683
BODY	7.42	1	7.42	2.68	0.1067
error	171.64	62	2.77		

Figure 5-56: **Rms Torque Command ANOVA (subject 3)**

TRACK	FXR	FYR
1	21.50	19.11
2	23.02	20.98

BODY	FXR	FYR
1	22.00	20.85
2	22.60	19.24

MON	FXR
1	23.20
2	21.41

Figure 5-57: **Rms Force Mean Values (subject 3)**

type of force and by subject. In general, there are no significant trends by day, except that some subjects may tend to use more of a particular command on the later days. Possibly this is a learning effect; subjects may grow equally comfortable with all commands or more comfortable with some. Possibly this is a strategic decision. As the subjects attempt to balance the translational and rotational tracking strategies, they tend to use more of a particular command. Except for the equally declining trends for subject two, there are no other declining trends. Perhaps a number of subjective observations made by this investigator over the course of the experiment may shed some light on the trends and the strategies employed by each subject. Subject one was observed to use more frequent but shorter duration joystick deflections on later days, apparently in an attempt to make more frequent tracking corrections. The success of this strategy may be indicated by Figure 5-16, demonstrating a decreasing separation by day, while Figure 5-31 indicates an increasing trend in direction changes. Subject two tended to use less frequent, short duration commands. Particularly on later days, this subject tended to track by establishing a smooth velocity to match that of the target. The strategy of subject three was noticeably different. This subject tended to use longer duration but less frequent joystick commands, the net result being larger net force and torque commands overall. These force and torque commands are

DAY	SUBJ 1			SUBJ 2		SUBJ 3		
	FXR	FYR	TZR	FXR	FYR	FXR	FYR	TZR
3	24.18	19.05	11.44	14.70	16.10	21.99	22.27	4.43
4	23.58	21.62	10.49	13.89	13.16	22.86	19.16	5.72
5	24.53	22.62	10.57	9.20	9.99	21.82	17.33	6.28
6	28.56	28.05	13.27	11.17	10.56	21.35	20.18	6.76

Figure 5-58: **Rms Force Mean Values (all subjects)**

TRAJ	SUBJ 1		SUBJ 2		SUBJ 3		
	FXR	FYR	FXR	FYR	FXR	FYR	TZR
1	24.06	23.13	10.96	11.93	22.40	19.91	5.34
2	24.74	22.30	11.92	11.46	20.79	18.87	5.21
3	29.66	25.70	15.52	19.34	25.17	23.16	5.93
4	23.78	23.15	11.38	10.75	21.41	20.01	5.06
5	22.81	19.64	9.52	9.24	19.64	14.83	6.50
6	26.80	23.09	14.14	12.00	24.15	21.62	6.75

Figure 5-59: **Rms Force Mean Values (all subjects)**

valuable indicators of operator strategy.

One final reference is made to the differences between trajectories. Figure 5-59 indicates that trajectory three caused the greatest use of joystick commands. The trajectory plots of Appendix A indicate that trajectory three has the longest route and thús travels at the fastest speed. In order to keep up, subjects increased the amounts of forces commanded.

Chapter 6

Discussion and Conclusions

This chapter presents a summary of the results discussed in Chapter 5 and an interpretation of the strategies and techniques of the human operators. Some conclusions are made relating to the performances and strategies to the primary factors of the investigation: the type of display, the use of head tracking and the addition of a body representation as a visual cue. The limitations of the virtual environment teleoperation simulator are discussed and the overall experimental design is evaluated. Recommendations for future studies with virtual environments are included.

6.1 Summary of Results

In summary, a virtual environment teleoperation simulator was designed and implemented. The simulator includes a computer based dynamic model of a teleoperated robot and the hardware (control station and displays) necessary for a human operator to observe the robot's environment and control its motion. The presence of a human operator in the system gives rise to issues of performance. The primary objective of this thesis is to determine what characteristics of the display which presents the environment allow the operator to better control the teleoperated vehicle. In an effort to define the study and obtain quantitative results, the display issues have been reduced to three primary factors. The first issue is the use of monitor and head mounted displays to view the environment. The second issue is the use of head tracking to alter the perspective of the view into the remote environment. The third issue is the addition of a visual representation of the vehicle body to the displayed image of the environment. Experimentation with human subjects performing target tracking tasks in the simulator has provided a number of results for consideration.

The advantage of running a computer based simulation is that a large volume of data is generated which can be used later to reproduce the experimental conditions for all subjects and all runs. A large amount of preparation and analysis in this study was related to how to manipulate this data to accurately represent the performance of the subjects. For a number of reasons, no single number was derived to measure this performance. Instead, a few performance metrics were introduced, including the actual commands made by operators at the joysticks and head tracker. Hopefully, reason as well as analysis have validated these choices. Clearly there are many alternatives not considered nor included.

Considering the target tracking task in the chosen virtual environment, what are the conclusions with respect to both tracking strategy and to the types of displays used? It was initially postulated that a robust tracking strategy would make use of both translational and rotational motion. In fact, the environment was designed and the tracking goals established to lead operators in this direction. It was hoped that a balanced strategy would highlight the performance differences resulting from the interesting factors, namely the monitor versus head mounted display, the body representation and head tracking. Based upon the balance of force and torque commands used, and the performance results for separation and angular offsets, subjects did develop balanced strategies. However, the single most significant factor in the strategy balance is the target trajectory itself. Basically, the velocity of the target determines the amounts of translational and rotational commands used. The two command types include the translational joystick commands and the rotational torque and head tracker commands. A fast moving target is more difficult to track by position. As a result, when further away from the target, its image appears smaller on the screen, and thus requires less rotational command to keep it completely in view. Fortunately, the relative amounts of each command seem to diminish equally.

Thus, the pooling of all trajectory results does not confound the overall results.

This leads to analysis of the display parameters. First, how do performance and strategy differ with the use of the monitor display versus the head mounted display? The surprising result is: very little. Not only do subjects perform nearly identically in terms of the derived metrics (separation, velocity offset, change of direction, forces used), but they do not significantly alter their strategic balance of translational and rotational tracking. There was some expectation that this would not be so. Remember that the hmd creates a stereoscopic wider field of view as opposed to the flat narrow monitor display. It was expected that operators would take a slightly different approach to tracking under the hmd. Perhaps increased depth perception would allow them to move up closer to the target. Perhaps the obstacles could be more easily avoided, making rotational control less necessary. There were no indications that this attempt to improve telepresence caused any strategy or performance differences. It is interesting to consider how operators would perform in a real environment when placed in the "driver's seat" of the vehicle. Some explanation of these results may be derived from the limitations of this particular hmd device and of the chosen task and environment, to be discussed.

The second display parameter of interest is the head tracker. One clear result is that head tracking increases the amount of rotational tracking compensation. The results for change of direction indicate that operators alter their orientation more frequently with head tracking. One explanation is postulated: as an operator turns their head from side to side, they attempt to compensate for the apparent rapid rotation of the environment about them by rotating their vehicle. They are possibly confusing the change in perspective caused by turning their head with the change caused by a rotation of the vehicle. Interestingly, and significantly, the addition of a body representation affects this result. When the body, which is fixed relative to the vehicle, is present, operators make less use of head tracking and make fewer direction changes.

The addition of a fixed body visual reference seems to have an effect on the overall tracking strategy for one significant reason: the body frame effectively reduces the monitor screen size. The body representation resulted in larger separations, larger orientation errors (velocity offset) and fewer direction changes. The strategy when tracking the target seems to be to try to stay a certain distance away and to keep it fully in view. When the body is added, operators must move further away to keep the target within the body frame. At a larger distance, it also takes less rotational effort to keep the target in view, hence these results.

6.2 Conclusions

Overall, how do the six display configurations compare? Subjective results of the post-test questionnaires (Appendix B) indicate that hmd configurations without the body representation were ranked more difficult than all others. Hmd display was ranked slightly more difficult than monitor display, on average. While head tracking under the hmd does not appear much different than either hmd without it or the monitor display, the body representation appears to make head tracking easier.

The primary question is which display configuration results in best human operator performance. Of the three factors, the addition of a body representation seems to have the largest effect. It seems to improve performance slightly but mainly causes operators to adopt a more stable control strategy. For instance, operators are able to stay slightly further away from the target but track it better in orientation, as well as use more precise force commands and corrections. Operators make less extreme use of head tracking with the body; they tend to look straight ahead with slight turns to each side rather than greater rotations from side to side. The body representation provides more information about obstacles locations, relative to the vehicle. When the wireframe outline of an obstacle intersects the solid body frame, the location and size of the intersection provides the cue of position and distance of the obstacle.

As for the other display factors, monitor type and head tracking, the results are mainly specific to the experimental parameters, particularly subject. Each of the three subjects adopted a somewhat unique tracking strategy. Consequently, results for each subject indicate slightly different configuration preferences. However, the following generalizations appear certain regarding virtual environment teleoperation. First, the type of display (monitor, hmd) does not cause operators to significantly alter their control strategy. However, modifications to the image (change in view due to head tracking, body representation) do cause changes in strategy and performance. The exact changes appear to depend on three factors: the type of task, the form and view of the environment and the control devices present. It is clear from the variations caused by the six different target trajectories that the nature of the task causes the greatest variation in performance and strategy. Tracking tasks, slalom tasks, dextrous tasks and others each require specific strategies. Factors such as head tracking and a body representation will benefit each to a different degree. Once the task is defined, the way that the environment is designed and presented to the operator then determines performance and strategy. Specifically, if the camera had been placed on the target or on a fixed mount within the environment rather than on the moving vehicle, tracking strategy would probably have differed. Finally, the control devices (joysticks and head tracker) determine the types of commands used by operators. For instance, operators lean or push forward on a joystick more often than pull back, in the configuration adopted. Such a tendency could be costly in certain circumstances.

6.3 Limitations and Recommendations

Consideration of the virtual environment teleoperator leads finally to a description of the system limitations. These limitations arise in two forms: regarding the harware and system components and regarding the environment and task design. The main system limitation is graphical processing capabilities. It is necassary to abandon detail and image complexity in favor of non-lagging and smooth animation. Current images use only wireframe, monochrome figures. The addition of color, solid modelling, texture maps, illumination and shading would create a more realistic view. While these are all possible with this system, the frame rate of the simulation decreases by orders of magnitude with their use. Further system limitations are the capabilities and resolutions of the displays. The VPL hmd provides extremely low resolution; individual pixels are noticeable. State of the art displays offer vastly improved resolution, currently up to 1024 $\times$ 768 pixels per eye, with color. The issue of time lag, once a huge problem with electromagnetic sensor devices, was solved with the potentiometer based head tracker. However, the device is intrusive, being attached to the operator and limiting their freedom of motion. The system is currently configured to create the illusion of depth by creating a binocular parallax of the left/right eye perspectives. Another depth cue is the use of motion parallax, where head motion from side to side changes the viewing perspective to indicate depth. Finally, the hmd itself is not comfortable for periods longer than 20 to 30 minutes. Subjects did complain of some eye soreness. The ideal virtual environment simulator is one which convinces a person that they are really within the environment without noticeable and intrusive links back to reality. It is the difference between being seated and looking out a window and actually being seated in a chair suspended in mid-air outside your window. In the first case, you can only imagine or extrapolate what the environment outside your window looks, feels, sounds and smells like. The addition of other types of interfaces, such as proprioceptive feedback for position and pressure are not far beyond the scope of this system.

A large amount of work went into designing the virtual environment and creating a task to highlight the differences of the display configurations. Space teleoperation was chosen in order to link the system back to practical applications. The dynamics modelled for the vehicle are very general. The view of the environment can be modified by simply changing camera positioning and perspective. As discussed, the environment was simplified to allow only three degrees of freedom of motion, within a plane. Despite this, the type of teleoperation implemented closely resembles true teleoperation of a free-flying vehicle. The environment and tasks are somewhat arbitrary when compared to true teleoperation. However, the goal of the study was not particularly to mimic true teleoperation, for even the uses and applications of real systems are numerous and not well defined. The goal then was to design a task to obtain quantitative comparisons between a number of factors such as display type and head tracking. The tracking task is a good one in that it is well defined and can be clearly expressed to an operator. The limitation is in obtaining well defined performance measurements. The obstacles were added to encourage head tracking but their effectiveness is difficult to measure. The balance of position and orientation tracking strategies is also difficult to measure. The amount of attention and control devoted to each varies over the course of a run and is not quantifiable. In recommendation, it may be more useful to design a number of specific tasks which highlight or require a single type of operator performance rather than a more difficult general task. The use of only three human subjects may be considered a limitation. However, the wide variability between subjects indicates that pooled results are not as convincing as good, clear results for individuals. Anticipation and verification of the learning period is the most important factor in achieving stable performance by subjects.

The virtual environment teleoperation simulator described in these pages is quite robust for numerous applications. Simple substitution and addition of hardware components can improve the system by lowering its limitations. The structured framework enables ongoing development and investigation. Of course, rapidly changing technology can make components obsolete but a systems approach to design can preserve much of the foundation. As virtual reality and virtual environments advance from concept to concrete, fundamental investigations such as this are necessary to ensure that humans remain comfortable and productive components of the system.

Appendix A

Target Trajectories

The six target trajectories are designed by summing three periodic waveforms. The first three use sinusoids while the last three using sawtooth waveforms. The view of the trajectory maps is from above the plane of the environment. The vehicle is centered on the grid and the target is the other larger box. The smaller boxes are the stationary obstacles. The target follows the trajectory route from the pictured initial position to the end over the 90 seconds of a run.

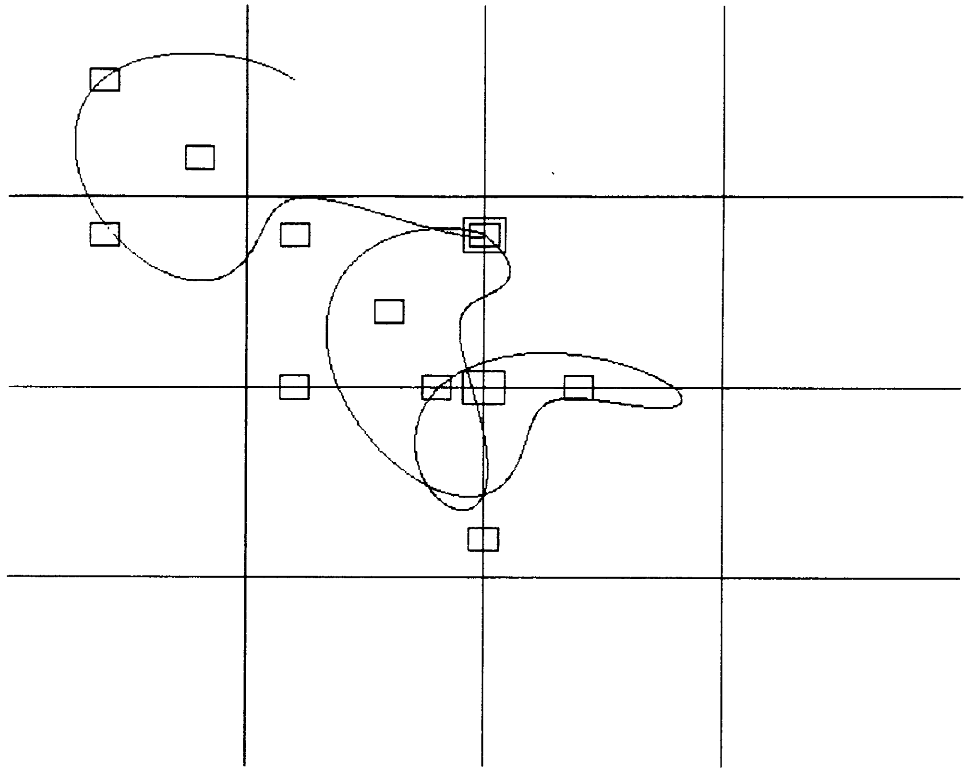

Figure A-1: **Trajectory 1**

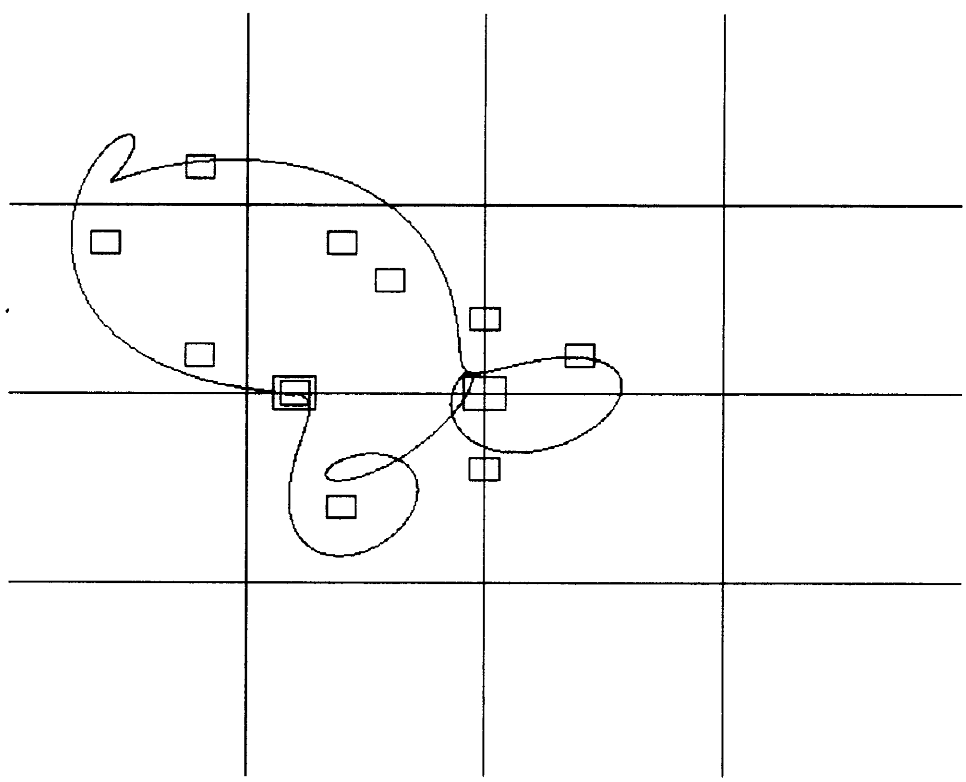

Figure A-2: **Trajectory 2**

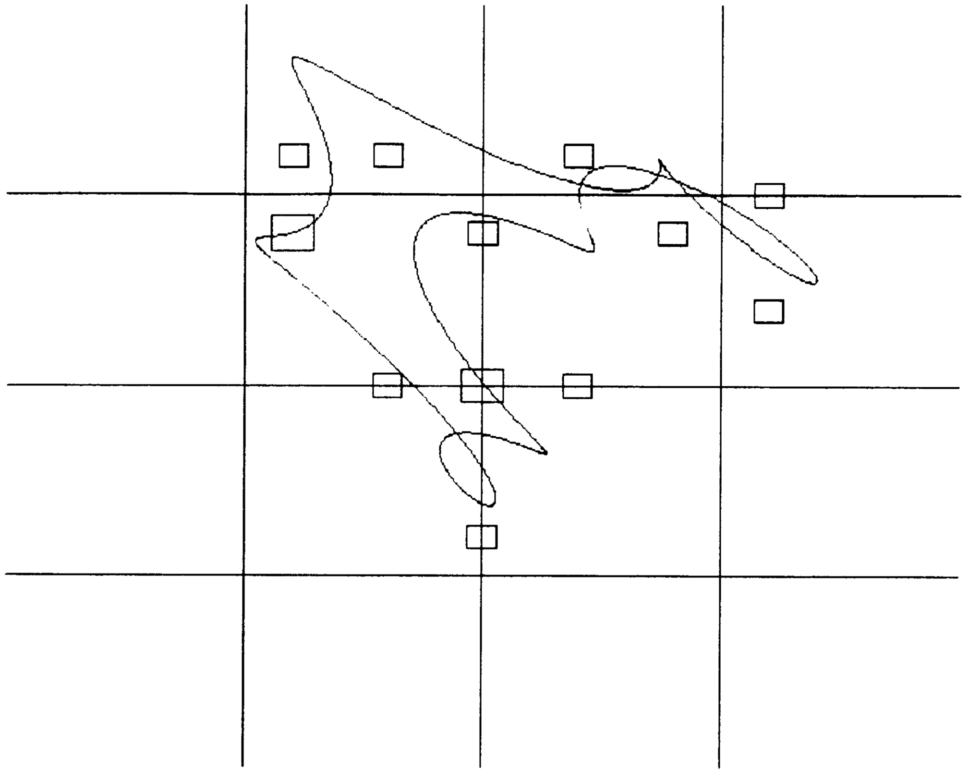

Figure A-3: **Trajectory 3**

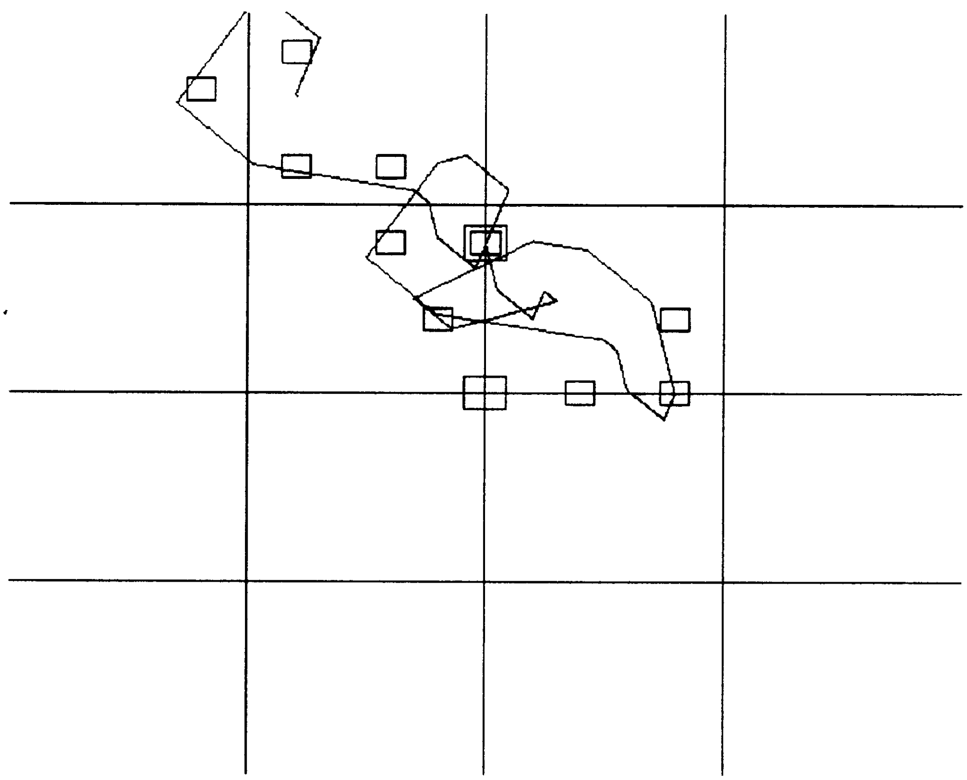

Figure A-4: **Trajectory 4**

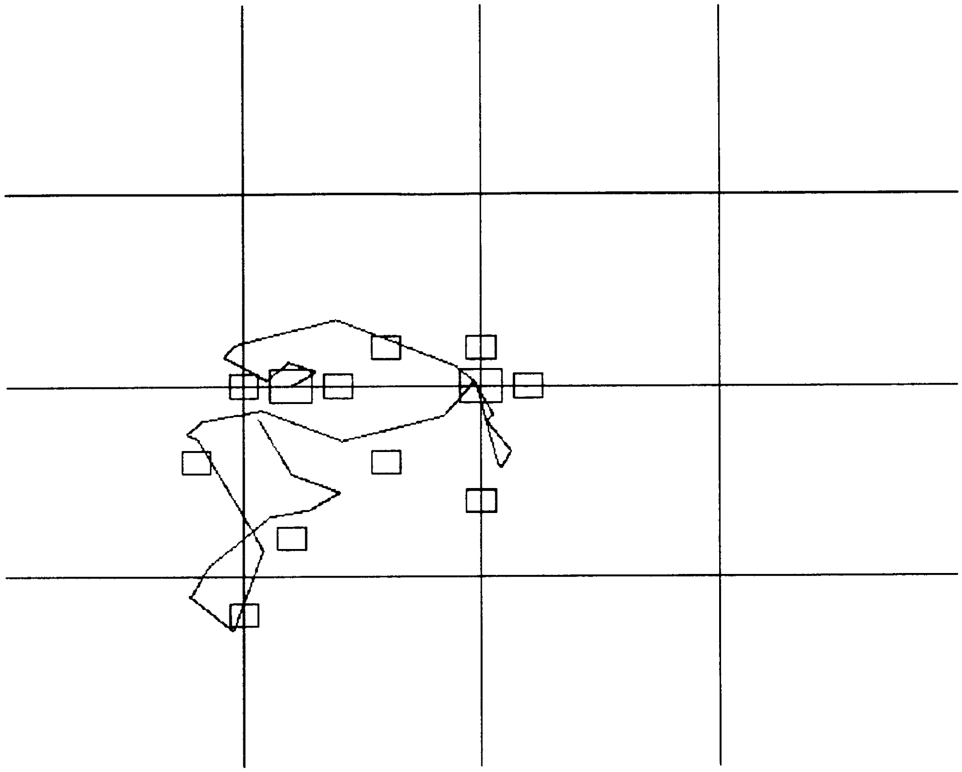

Figure A-5: **Trajectory 5**

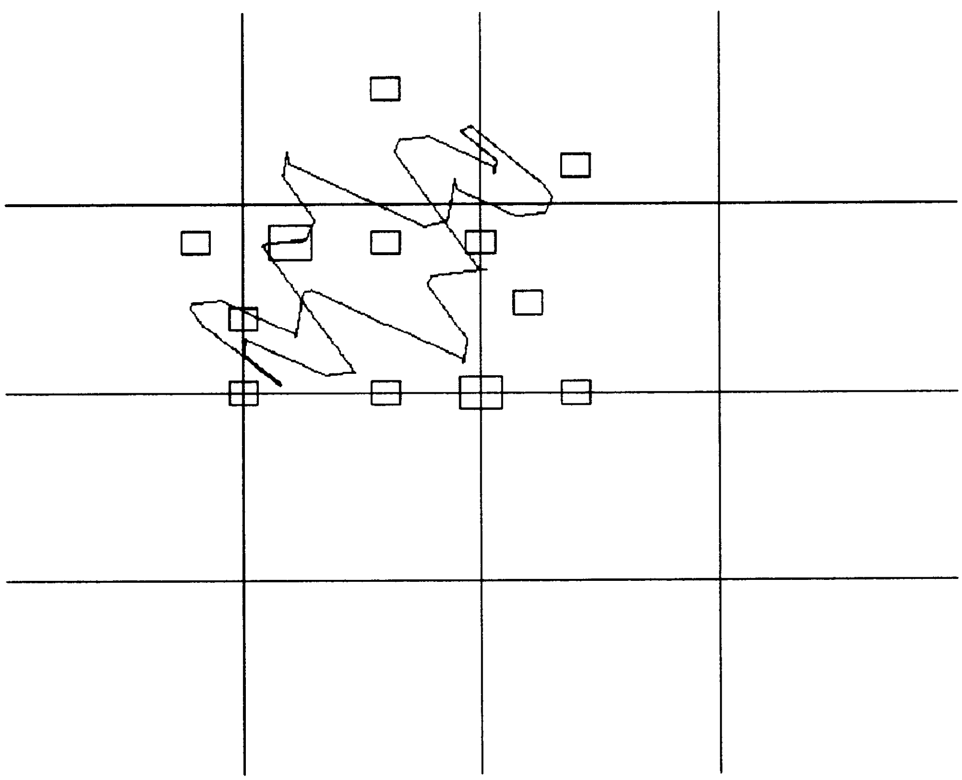

Figure A-6: **Trajectory 6**

Appendix B

Subject Questionnaires

B.1 General Questions

The following questionnaire was administered to each subject prior to the first session of experiments.

Subject Questionnaire

Please circle the one response to each question which best describes your condition. Please answer all questions. Feel free to ask for clarification of any question.

Name:

Age:

1. Handedness: Right / Left / Ambidextrous

2. Do you wear glasses or contact lenses, and for which eye condition?

No, perfect vision.

No, but I have the following eye condition or vision irregularities:

Yes, I am nearsighted (can see well only up close)

Yes, I am farsighted (can see well only far away)

Yes, for other reason (describe)

3. How many hours do you typically drive in a week?

None at all,

0 - 1 hour,

1- 5 hours,

5 - 10 hours,

more than 10 hours. I estimate ___ hours per week.

4. When you are driving an unfamiliar car or one belonging to someone else, do you prefer to:

Drive more carefully or slowly than usual at all times?

Drive more carefully or slowly at the beginning only?

Drive just as you would your own car?

Push the car a little to test it's performance?

Drive the car all-out to test it's limits?

5. Do you have a pilot's license, and if so how many hours of flight time do you have? If you have flown a flight simulator, please indicate.

No.

Yes. I have piloted ___ hours.

6. Do you play action type video games (e.g. Space Invaders, Tetris), and if so how many hours per week?

No.

Yes, less than 1 hour per week.

Yes, 1 to 5 hours per week.

Yes, more than 5 hours per week.

7. How often do you experience the following? Please circle a number, with 1 meaning never and 5 meaning very often.

Motion sickness:	(Never) 1 2 3 4 5 (Very often)
Nausea:	(Never) 1 2 3 4 5 (Very often)
Headaches:	(Never) 1 2 3 4 5 (Very often)
Blurred vision:	(Never) 1 2 3 4 5 (Very often)
Tired/sore eyes:	(Never) 1 2 3 4 5 (Very often)
Loss of balance:	(Never) 1 2 3 4 5 (Very often)
Dizziness:	(Never) 1 2 3 4 5 (Very often)
Disorientation:	(Never) 1 2 3 4 5 (Very often)
Drowsiness:	(Never) 1 2 3 4 5 (Very often)

8. How many hours of physical activity do you participate in, per week? (e.g. fast walking, biking, running, sports)

None

0 - 1 hour

1 - 2 hours

2 -5 hours

more than 5 hours.

Eye-handedness test: Subjects were asked to pick up a cylindrical tube (12 inches long by 1 inch diameter) with each hand and look through it to read some text on a sheet of paper. Presumably, if the subject does not favour one eye, they will use their right eye with right hand and vice-versa for left.

Question	Subject 1	Subject 2	Subject 3
0	19	24	24
1	R	R	L
2	1	1	1
3	2	3	2
4	2	2	2
5	1	1	1
6	2	2	2
7.1	2	3	2
7.2	2	2	2
7.3	4	2	2
7.4	1	1	1
7.5	2	3	3
7.6	2	1	1
7.7	1	2	2
7.8	1	1	2
7.9	4	2	4
8	5	4	2
9.R	R	R	R
9.L	L	L	L

Figure B-1: **Questionnaire Results**

B.2 Pre-test Questions

The following questionnaire was administered to each subject prior to each session of experiments.

Name:

Time of Day:

1. To what degree are you experiencing any of the following at this time?

Motion sickness:	(Never) 1 2 3 4 5 (Very often)
Nausea:	(Never) 1 2 3 4 5 (Very often)
Headaches:	(Never) 1 2 3 4 5 (Very often)
Blurred vision:	(Never) 1 2 3 4 5 (Very often)
Tired/sore eyes:	(Never) 1 2 3 4 5 (Very often)
Loss of balance:	(Never) 1 2 3 4 5 (Very often)
Dizziness:	(Never) 1 2 3 4 5 (Very often)
Disorientation:	(Never) 1 2 3 4 5 (Very often)
Drowsiness:	(Never) 1 2 3 4 5 (Very often)
Tired/sore body:	(Never) 1 2 3 4 5 (Very often)

B.3 Post-test Questions

The following questionnaire was administered to each subject following each session of experiments.

Name:

1. To what degree are you experiencing any of the following at this time?

Motion sickness:	(Never) 1 2 3 4 5 (Very often)
Nausea:	(Never) 1 2 3 4 5 (Very often)
Headaches:	(Never) 1 2 3 4 5 (Very often)
Blurred vision:	(Never) 1 2 3 4 5 (Very often)
Tired/sore eyes:	(Never) 1 2 3 4 5 (Very often)
Loss of balance:	(Never) 1 2 3 4 5 (Very often)
Dizziness:	(Never) 1 2 3 4 5 (Very often)
Disorientation:	(Never) 1 2 3 4 5 (Very often)
Drowsiness:	(Never) 1 2 3 4 5 (Very often)
Tired/sore body:	(Never) 1 2 3 4 5 (Very often)

2. How would you subjectively rate the difficulty of the test sections (1=not difficult, 5=very difficult)? Please rank them from most difficult (1) to least difficult (3).

Section 1:	(not difficult) 1 2 3 4 5 (very difficult)	Rank____
Section 2:	(not difficult) 1 2 3 4 5 (very difficult)	Rank____
Section 3:	(not difficult) 1 2 3 4 5 (very difficult)	Rank____

		Day: pre-test (-) post-test (+)											
		1		2		3		4		5		6	
Sub	Q	-	+	-	+	-	+	-	+	-	+	-	+
1	1.1	1	1	1	1	1	1	1	1	1	1	1	1
	1.2	1	2	1	1	1	1	1	1	1	1	1	1
	1.3	1	1	1	1	1	1	1	1	1	1	1	1
	1.4	1	1	1	1	1	1	1	1	1	1	1	2
	1.5	1	2	1	2	2	3	2	3	2	2	2	2
	1.6	1	1	1	1	1	1	1	1	1	1	1	1
	1.7	1	1	1	1	1	1	1	1	1	1	1	1
	1.8	1	1	1	1	1	1	1	1	1	1	1	1
	1.9	1	1	1	1	2	2	2	2	2	1	1	2
	1.10	3	2	1	1	2	2	1	1	2	2	2	2
2	1.1	1	1	1	1	1	1	1	1	1	1	1	1
	1.2	1	1	1	1	1	1	1	1	1	1	1	1
	1.3	2	2	1	1	1	1	2	2	1	1	1	1
	1.4	1	1	1	2	1	1	1	1	1	1	1	1
	1.5	2	2	2	3	1	2	2	1	1	1	1	1
	1.6	1	1	1	1	1	1	1	1	1	1	1	1
	1.7	1	1	1	1	1	1	1	1	1	1	1	1
	1.8	1	1	1	1	1	1	1	1	1	1	1	1
	1.9	1	1	1	1	1	1	1	1	1	1	1	1
	1.10	2	2	2	2	1	2	1	1	1	1	1	1
3	1.1	1	2	1	1	1	1	1	1	1	1	1	1
	1.2	1	2	1	1	1	1	1	3	1	2	1	1
	1.3	1	3	1	1	1	1	1	2	1	1	1	1
	1.4	1	1	1	1	1	1	1	1	1	1	1	1
	1.5	1	3	1	2	1	2	1	1	1	1	1	1
	1.6	1	1	1	1	1	1	1	1	1	1	1	1
	1.7	1	3	1	3	1	3	1	3	1	1	1	2
	1.8	1	1	1	1	1	1	1	1	1	1	1	1
	1.9	1	2	3	3	1	3	1	1	1	3	1	1
	1.10	1	1	1	1	1	1	1	1	1	1	1	1

Figure B-2: **Pre and Post-test Questionnaire Results**

		Day: difficulty (D) Rank (R)											
		1		2		3		4		5		6	
Sub	Slot	D	R	D	R	D	R	D	R	D	R	D	R
1	1	4	1	2	2	2	2	3	3	2	2	3	1
	2	3	2	3	1	3	1	3	2	3	1	3	1
	3	3	3	3	1	3	1	4	1	2	2	2	2
2	1	2	3	3	2	3	1	2	3	1	3	1	2
	2	3	2	5	3	3	2	3	2	2	2	2	3
	3	3	1	3	1	2	3	4	1	4	1	1	1
3	1	3	3	4	2	4	1	3	3	3	3	5	1
	2	4	1	4	1	3	2	4	1	3	2	3	3
	3	3	2	3	3	3	3	4	2	5	1	3	2

Figure B-3: **Post-test Questionnaire Difficulty Results**

Appendix C

Introduction and Instructions

Thank you for volunteering for this experiment. You will be participating in a series of tests which will produce data for scientific research. Your cooperation is greatly appreciated. Feel free to ask questions at any time and please notify me immediately if there are any problems.

The experimental framework is a computer simulation of a remotely-operated vehicle in planar environment. You will have control of the motion of this vehicle using a pair of joysticks. You will be able to view your environment through a camera mounted on the front of the vehicle. The left joystick allows you to command forward-backward and left-right accelerations while the right joystick allows you to control rotational velocity. Please note that after you command an acceleration, your vehicle will maintain its resulting velocity in a given direction much like a puck on ice. However, after you command a rotational velocity, your vehicle will then stop rotating.

You will perform the tests under six different display conditions:

1. Monitor: You will view the environment through a camera which is fixed and mounted on the front of your vehicle.

2. Monitor with body representation: Your camera is fixed but there is a representation of your vehicle body superimposed on the screen, with cross-hairs. It is as if you are looking out through a car windshield.

3. Head-mounted display: The VPL Eyephones is worn on your head and consists of two viewscreens placed directly in front of your eyes. This is intended to give you a stereoscopic view of your environment from the front of your vehicle.

4. Head-mounted display with body representation: As above, with vehicle body frame and cross-hairs visible.

5. Head-tracking display: This is a stereoscopic head-mounted display in which your head movements allow you to control the direction in which you look. Please note that your head movements do not affect the motion of the vehicle.

6. Head-tracking display with body representation: You will see the frame of your vehicle body. This frame is rigidly attached to the vehicle, so as you turn your head, you will be viewing it from different orientations.

Your task will be to track a moving target in a planar environment. The environment consists of mountains off in the distance and randomly scattered sticks along the ground. The target is a large cube with a smaller cube centered within it. All objects are represented as line figures. You will be able to move through the target itself, but you may lose sight of it when you do. Slightly below the plane are a number of solid obstacles. These are represented with lines as tall columns, but they are solid! If you hit them, you will bounce off and find yourself facing a random direction.

These are your tracking goals, all having equal importance.

1. Always be as close to the target as possible.

2. Always be moving towards the target.

3. Always have your vehicle body facing the target.

4. Never hit an obstacle.

Although you must move towards the target, and have the vehicle face the target (i.e.. have the target centered in the cross-hairs), you may look in any direction when you have that freedom with head-tracking. When you lose sight of the target, which may happen if you hit an obstacle, do not panic. Simply re-acquire the target and continue tacking to your best ability. There is no perfect way to accomplish all of your goals. In some circumstances, you may have to sacrifice some performance on one in order to maintain acceptable performance on another.

The full experiment will consist of six 45 minute sessions spread over three weeks. At each session, you will perform under three of the six display configurations. For each configuration, you will have six 90 second runs, with a short pause between runs. You will then have a longer pause between configurations. You will be asked to respond to a short questionnaire before and after each session.

When all subjects have completed all their tests, I'll take everyone out for lunch. Thanks for your help!

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