A Virtual Environment System for Spatial Orientation Research

by

John de Souza

Submitted to the Department of Electrical Engineering and Computer Science
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Abstract

A prototypic Virtual Environment System (VES) was developed for spatial orientation research and as a reference system for the 1998 Neurolab project. The VES was configured using a DOS based PC (100MHz Pentium), two SPEA i860 FIRE boards, an Eyephone I Head Mounted Display (HMD), and an ADL-1 electromechanical head tracker. The software was developed using the World Tool Kit C library.

A furnished room scene was presented to 12 subjects rotating about their roll axis with the head in various orientations. When erect and not using the head tracker, 75% of them experienced full tumbling. Compared to Howard and Childerson's study using a real room, this confirmed the ability of the VES to induce illusory rotation. Using head tracker to follow a peripheral object, 17% felt full tumbling and 50% no illusion possibly because of sensory conflict due to head tracker lag. In both the supine and inverted positions the percentage of tumbling was lower (42%) than in erect. In the supine position this was possibly due to the conflict between the earth-horizontal visual down and gravity, inspite of the axis of rotation being aligned with gravity. In the inverted position it may have been due to the unfamiliar haptic cues orthogonal to the axis of visual rotation.

The VES was evaluated using the furnished room (115 polygons). A performance of 2104 polygons/sec at 18.3 updates/sec was achieved when rendered using flat shading, texture mapping, and perspective correction. When the room was rotated, the textures sparkled and WTK's non-uniform update rate interrupted smooth motion. The ADL-1 head tracker had a 55ms lag as it could only be sampled as fast as the update rate. Innacuracies in the euler angles from the ADL-1 were limited by restricting head movement. A device driver was written to use absolute orientational data from the head tracker to update the viewpoint and avoid drift in its orientation. Head tracker noise, magnified by the HMD's coarse pixelization, resulted in scene jitter.

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Title: Director Man Vehicle Lab

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Chapter 1

Introduction

The objective of this thesis was to develop a Virtual Environment System (VES) that can serve as a prototypic system for spatial orientation research. The system will also serve as a reference system for a study being conducted by NASA on human visual orientation. This study is aimed at better understanding how humans transform spatial orientation cues from egocentric to exocentric frames so as to perceive orientation and motion both linearly and angularly. A series of 1-G and 0-G experiments in both real and virtual environments have been proposed. The VES will help resolve certain technical and scientific issues associated with the development of the NASA Virtual Environment Generator for the 1998 Spacelab mission called Neurolab.

Humans determine self-orientation using information from the eyes, vestibular organs, and haptic receptors around the body. On earth, gravity provides an omnipresent cue that can be used to help orient the world around us. In space the absence of gravity results in the need for a different interpretation of the signals received from the sensory organs. Results from previous studies ([13], [10]) have shown that astronauts initially become more dependent on visual and haptic cues than on vestibular information for judging orientation in conditions of micro-gravity. Since the crewmembers are not anchored to the floor, they can move around in three dimensions and view their surroundings from a variety of different body attitudes. Spacelab crewmembers have described a variety of striking and labile Visual Reorientation Illusions (VRI) in which "floors", "walls", and "ceilings" exchange their subjective identities. Some have also experienced "inversion illusions", although less frequently, when working in areas of the shuttle that have strong symmetries in the ceiling-floor direction. These illusions have been shown to trigger space sickness, disorientation, and a variety of human factors problems. Thus it is of practical operational importance to study human orientation processing to better understand these illusions.

Many of the experiments hitherto performed to study human spatial processing involved either rotating or tilting objects, subjects, and sometimes even rooms. Although the illusions generated by these are very convincing, the cumbersome nature of the experimental setup is limiting. To study the effects of visual stimuli (frame, polarity, and motion) in 0-G, Oman et al.[12] have proposed the use of a VES instead of a real environment. They hypothesized that visual reorientation and inversion illusions can be created by using a controlled stimulus provided by a VES, in subjects susceptible to such illusions. A VES is an attractive alternative to a real environment as it allows the possibility of rapid experiment development, the ability to quickly and easily change experimental parameters such size and shape of room, and axis of rotation. The VES also requires much less physical space, making it feasible to repeat such experiments in the confines of Spacelab.

This thesis describes a prototypic VES that was developed for spatial orientation research. The performance of the system was evaluated using a scene of a furnished room containing 115 polygons, including 16 textured polygons. A Virtual Rotating Room (VRR) experiment was used to evaluate the ability of the VES to induce illusions by comparing it to a similar experiment performed by Howard and Childerson[7] in a real room. The effects of head orientation and point of regard on induced self tilt and self motion were also studied.

The thesis is organized as follows. Chapter 2 provides the background material. Chapter 3 describes the VES. Chapter 4 describes the virtual environment and the VRR experiment. Chapter 5 details the performance of the system and presents the results of the VRR experiment. Chapter 6 discusses these results and critiques the VES. Chapter 7 summarizes the work done and makes recommendations for future research.

Chapter 2

Background and Significance

2.1 Orientation

Humans use vision, proprioception, and information from the vestibular organs to judge the orientation of their bodies with respect to gravity[4]. This thesis considers the contributions of vision and the vestibular organs to the perception of self tilt and self motion.

There are at least three types of information that we extract from visual data in order to determine orientation [7]. These are: the polarity of objects around us, the orientation of the visual frame, and visual motion. The following sections briefly describe the influence of these three types of visual information on perceived self orientation.

2.1.1 Visual Frame

Normally one can infer the orientation of an object by comparing it to a reference of known orientation such as a wall or floor. Such objects whose orientations are normally perceived as invariant provide what is known as a visual frame of reference. Since the visual frame is unchanged when rotated through 180°, it only provides information on tilt but not on which direction is up or down. Tilting the frame of reference has the same effect as resetting the zero mark for orientation judgment.

Witkin and Asch (1948) showed that illusory self tilt can be induced in a subject using a tilted luminous square frame. In their experiments they tilted a square, with 1 m sides, 28° either to the left or to the right about the subject's frontal plane. The subject then set a rod to the apparent vertical. It was found that the tilted frame induced a 6° feeling of self tilt in the direction of the tilted frame.

2.1.2 Visual Polarity

Many everyday objects such as a table, car, house, and coffee cup are visually polarised, having a distinct "top" and "bottom". We are accustomed to viewing such mono-oriented objects in a particular orientation with respect to gravity. The orientation cue given to us by the polarity of these objects constitutes the visual polarity stimulus.

When all the polarised objects in view are tilted in the same direction by the same amount, the viewer feels a sense of self tilt. Wertheimer (1912) showed that when viewing a room through a tilted mirror, the room soon appears upright to the subject. It was reported by Kitahara and Uno (1967) that residents in buildings that were tilted by as much as 8° by an earthquake perceive the room as upright. Witkin and Asch (1948) showed that an illusion of self tilt can be induced in erect subjects by making them view a stationary tilted room. These effects are due to visual frame and visual polarity stimuli.

2.1.3 Visual Motion

It has been found that the motion of objects can effect our judgments of self orientation. Held (1975)[2] and Howard (1988)[6] showed that a feeling of self tilt is induced in a subject when viewing a large display of dots rotating in the frontal plane. Since there were no polarised objects or visual reference frames present in the display, the effect was solely due to visual motion. The induced self tilt rarely exceeded 20°.

Howard (1988), in an effort to quantify the sensation, placed subjects in a sphere with a 9 ft diameter, capable of rotating about the roll axis. Using this he was able to induce an average of 25° of self tilt, with some subjects experiencing up to 90° of self tilt.

2.2 Haunted Swing Illusion

When the effects of the three visual stimuli are combined, some very striking illusions can be induced. A good example of this is found in a fairground attraction built in Los Angeles towards the end of the last century called "The Haunted Swing"[17]. The device used consisted of a large fully furnished room with an axle through the centre about which the room pitched. Hanging from the axle was a gondola in which ardent thrill seekers sat with their heads a few feet below the axle. When the room was rotated about the axle with the gondola stationary, all those in the gondola felt as if the room were stationary and the gondola was rotating.

Since the heads of the observers were not along the axis of rotation, the haunted swing effect illustrates VRI but does not prove that visual factors overcame the restraining influence of inputs from the vestibular organs. This is because even if the gondola were the one rotating, the otolith organs would not register a real rotation and therefore there would be no conflict between the otolith and visual input (for a more detailed explanation see Howard and Childerson's paper (1993)[7]).

Kleint (1937) experimented with the effects of rotating a furnished room through 360° about the earth horizontal, with the subject's head along the axis of rotation. When the room was rotated, some subjects experienced a feeling of total self rotation and some felt only a side-to-side oscillation.

In later experiments Howard et al. began quantifying these sensations. To study the contribution of visual stimuli to the illusion of self tilt and self rotation, Howard and Childerson performed a series of tests using a room that rotated about the subject's roll axis[7]. For part of the experiment the room was presented at a static tilt angle after which the subject set a rod to the perceived vertical. During the other part of the experiment a room was presented to the subject continuously rotating at a constant velocity about the roll axis. The subject's description of the sensation was then used to categorize the response. Three types of rooms were used for these experiments, a dotted sphere, a dotted room, and a furnished room.

The Virtual Rotating Room (VRR) experiment described in this thesis was an adaptation of the part of Howard and Childerson's rotating room experiment performed with a furnished room. The following section describes this part of their experiment.

2.3 Howard and Childerson's Furnished Rotating Room Experiment

2.3.1 Experiment Description

The subject was presented with a real furnished room rotating continuously about the roll axis at 15°/sec for four complete revolutions. Verbal responses obtained from the subjects were used to categorize the data. The subjects were given a description of the following categories before each trial:

1. *Constant Tilt*: Subjects felt inclined about the roll axis at a constant angle in the opposite direction to that in which the scene was rotating.

2. *Alternating Tilt*: Subjects felt as if they were rotating in the roll plane in antiphase to the motion of the scene to a certain limiting angle of tilt, then felt suddenly upright , then began tilting again.

3. *Full Tumbling*: Subjects felt they had tumbled completely through 360°.

4. *Supine*: Subjects felt they were supine and looking up at the visual display which appeared to be in a frontal horizontal plane above them.

2.3.2 Stimulus

The subject was seated in a stationary box-shaped seat with the head near the centre of a 7 ft long cubic wallpapered room, with baseboards, linoleum, and ceiling tiles.

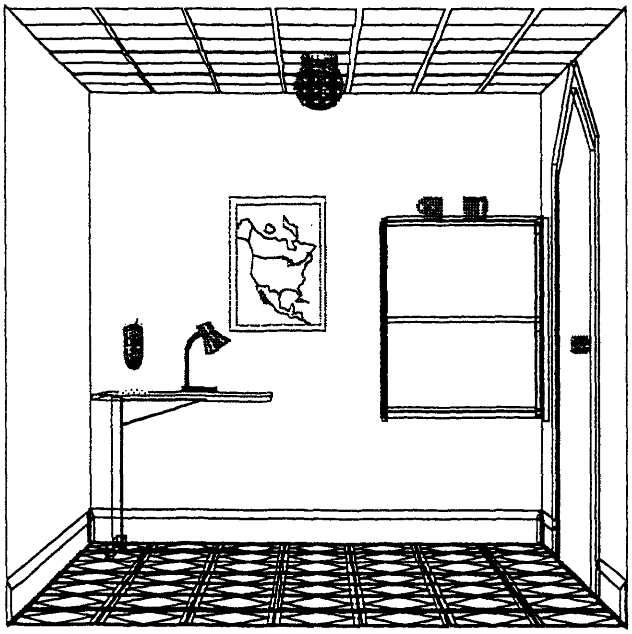

Figure 2-1: Model of Howard and Childerson's Rotating Room

The wall in front of the subject had a bookshelf with a cup and magazine cemented to it. There was a desk onto which a fake sundae and a desk lamp with a 40 W bulb were cemented. The wall on the left of the subject contained a window and the wall to the right contained a door and a picture. There was also a ceiling lamp with a 40 W bulb. A computer model of the room made by Oman is shown in Figure 2-1.

2.3.3 Results

A total of 30 subjects were tested, of which 18 (60%) experienced continuous tumbling, 7 (23.33%) experienced constant tilt, 4 (13.33%) felt as if they were watching the room rotate while in the supine position, and 1 (3.33%) felt as if he was both supine and tilted. Table 2.1 summarizes these results. A Cochrane Q test was applied to the data and showed that there were significant differences in the numbers of subjects showing constant tilt, alternating tilt, and tumbling among the stimulus conditions.

Table 2.1: System Specifications

Sensation	Number of Occurances	Percentage of Subjects
Full Tumbling	18	60%
Constant Tilt	7	23.33%
Supine	4	13.33%
Supine plus Tilt	1	3.33%

2.4 Head Orientation Effects on Tilt Sensation

Howard and Childerson performed the tests with the subject's head in the erect position. Earlier studies have shown that visually induced self motion about the earth vertical depends on the orientation of the head. Held et al.[2], presented subjects with a large circular visual display filled with dots rotating about an earth horizontal axis. Most subjects experienced a sustained sensation of self tilt rather than continuous rotation when their heads were in the erect position. Young et al.[19] used a wide field projected dot display in a flight simulator to show that the magnitude of self tilt in pitch and roll increased as the head was tilted away from the normally erect position, as if gravity sensing organs restrain vection sensations when in the familiar erect orientation with respect to gravity. This research was extended by Howard et al.[6] who used a 9 ft diameter sphere lined with black dots. The studies showed that visually induced self motion was the strongest when the stimulus rotated about an earth vertical axis. However, the stimulus in the experiments consisted only of visual motion. In this thesis we extended the study to include the effects of visual polarity and visual frame.

Chapter 3

Virtual Environment System Description

This chapter first compares the use of virtual versus real environments and then describes the Virtual Environment System (VES) that was used for the Virtual Rotating Room (VRR) experiment.

3.1 Virtual Environment

Charles Oman and Ian Howard [12] proposed that it might be possible to stimulate self tilt and self motion in subjects susceptible to them using virtual environments. The use of a VES for studying spatial orientation processing provides an experimental setup that can be easily taken to orbit on board Spacelab, enabling experiments to be performed in 0-G. The next section compares the use of real versus virtual environments for research on spatial orientation processing. This is followed by a discussion of some of the factors that influence the "immersiveness" of VESs.

3.1.1 Virtual versus Real Environments

Real environments, especially rotating rooms, tend to be physically large and require a substantial amount of time to build. In addition, some of their parameters are difficult to change, e.g., axis of rotation, size, maximum rotation speed, room acceleration, etc. A VES requires only the space for a computer and its peripherals. The initial cost of a VES can be high but the marginal cost of developing new environments is low. Different virtual environments can be developed rapidly, and changing test parameters such as axis of rotation, speed of rotation, type of rotation profile, lighting, viewpoint, etc., is relatively simple. While real environments are able to induce compelling illusions in subjects susceptible to them [7], the success of a VES in inducing illusions is dependent on the "immersiveness" of the system. The term immersiveness is used to refer to the degree of realism achieved by the virtual environment. The factors that effect the immersiveness of a VES have just begun to be studied and have not yet been well documented. Some of the factors include Field Of View (FOV), resolution, binocular overlap, texturing, shading, tiling, rendering speed, and lagtime. The following is a brief review of how these factors may effect the immersiveness of the virtual environment.

3.1.2 Factors Effecting Immersiveness of VES

Resolution

For a given display size the greater the resolution the less visible individual pixels of the display are, therefore, the more realistic the image appears. Resolution also limits the capability of the VES to accurately render the orientation of surfaces. High resolution displays also provide more detail thus aiding in the recognition of objects and in determining the orientation of polarised objects.

Shading

The proper use of shading can help eliminate some of the "cartoon" qualities of scenes. Shading can help discern the edge between two intersecting polygons of the same colour. These edges may constitute part of the visual frame. Shading can also be used as an orientation cue, since light sources are usually assumed to be "from above" ([5], [4]).

Tiling

Tiling describes a technique wherein multiple displays are used to create an image for each eye. As a result of the gaps inbetween the displays, each eye may see a stripe thus decreasing the quality of the virtual world. Since these artifacts remain invariant with respect to the head when the scene rotates, they constitute an unwanted rectangular visual frame. The orientation of this frame differs from that provided by the virtual environment and could interfere with the the results of the VRR experiment.

Texturing

Texturing is a method for increasing the realism of graphical objects by applying 2-D pictures to 3-D polygons. Texturing economically provides important detail. Since this thesis studies the effects of visual polarity, texturing is important in object recognition which utilizes the high acuity central foveal vision. This is in contrast to simple vection which is probably mediated by our peripheral vision.

Scene Update Rate and Variability

A minimum scene update rate of approximately 10-20 Hz is necessary for motion to be perceived as smooth and for motion parallax cues to support depth perception. Below this rate illusory motion or even simulator sickness may result [14]. Rendering speed is a function of the computational power of the machine and the complexity of the scene (measured in number of polygons, type of shading, texturing, etc.). The greater the computational power and the lower the complexity are, the smoother the motion of the scene is. Thus the use of a fast processor and graphics accelerators is recommended. Lowering the complexity of the scene increases the update rate but also detracts from the realism of the scene.

Variability in the scene update rate can result in a loss of vection, as it implies acceleration and deceleration of the head, which is unaccompanied by the corresponding semi-circular canal cues. The conflict between the actual and anticipated stimuli detracts from the vection illusion. The acceptable limits on the variability of scene update rate necessary in order to maintain vection are yet to be documented.

Head Tracker Lag Time

Lag time refers to the delay between the subject moving his head and the viewpoint of the virtual world being updated to reflect this change. If the head tracker has large lag times, the illusion of motion is destroyed. Non-smooth motion has been known to destroy vection, and would effect the results of the studies on perceived self tilt and motion. In addition, conflict between actual and anticipated signals from sense organs can induce symptoms similar to motion sickness ([11], [9]).

Field Of View and Binocular Overlap

Two of Ian Howard's colleagues, Jim Zacker and Rob Allison, recently studied the effect of different FOVs and binocular overlap on inducing self rotation using a rotating furnished room. They found (results conveyed through personal communication) that the percentage of subjects that experienced full tumbling changed from 31% to 80% when the binocular FOV was increased from 20° to full. They also found that changing the binocular overlap while maintaining the total FOV constant had no effect on the percentage of subjects that experienced full tumbling.

Colour and Stereo

The importance of colour and stereoscopic vision on the immersiveness of a VES has not yet been studied.

3.2 Virtual Environment System

Table 3.1 and Table 3.2 respectively list the hardware components and software packages used in developing the VES. Figure 3-1 shows the hardware components of the VES. The following sections describe the various components in detail.

Figure 3-1: The Virtual Environment System

Table 3.1: System Specifications

Component	Manufacturer	Description
Legend 836T	Packard Bell	Pentium 100MHz based computer
17SE	SONY	17" Monitor
Two i860 FIRE Boards	SPEA	Graphics Accelerators
Eyephone Model I	VPL Research	Stereo Head Mounted Display
ADL-1	Shooting Star Tech.	Mechanical Head Tracker

Table 3.2: Software Packages

Software	Manufacturer	Description
World Tool Kit-PC	Sense8	Virtual Environment C Library
High C	Metaware	C/C++ Compiler
TNT Dos-Extender	Phar Lap	DOS Extender

3.2.1 Packard Bell 100MHz Pentium Computer

A PC platform was chosen because it was able to meet the power constraint, of using less than 1000 Watts set on experiments to be run on Spacelab. In addition, hardware texturing, achieved through the addition of a graphics board, can be acquired at a reasonable cost. A SPEA FIRE graphics board costs $2600 whereas a Reality Engine graphics board for the SGI Onyx machines costs $40,000 or more.

As mentioned earlier, texturing was important because it enhanced the immersiveness of the VES, and provided detail that was important for object recognition. Unfortunately, a computational speed penalty must be paid to perform perspective correction on textures to correct for the distortion that occurs when the textures are viewed obliquely.

Recently there has been a lot of momentum aimed at developing graphic accelerator boards and graphics coprocessors for the PC platform, so this paltform will be well supported in the future. At the time of purchase the 100MHz Pentium was the fastest INTEL processor available.

3.2.2 SPEA i860 FIRE Graphics Accelerator Boards

The SPEA FIRE graphics accelerator board utilizes an INTEL i860 (33 Mhz) processor with 64 bit architecture and 40 MIPS. The board has 2 Mbyte Dual Ported VRAM, and 16 Mbyte DRAM, and also offers hardware antialiasing and texturing. The card was supported by Sense8, the manufacturer of World Tool Kit (WTK), thus allowing the FIRE boards to be easily interfaced with WTK. Since a stereoscopic Head Mounted Display (HMD) was used, two FIRE boards were necessary, one for each eye, in order to maintain acceptable performance.

3.2.3 Shooting Star ADL-1 Head Tracker

The ADL-1 Version 3.0, manufactured by Shooting Star Technology, is a 6 DOF electromechanical head tracker. An electromechanical head tracker was selected because it provided an inexpensive, relatively accurate, and low latency (could be operated up to 115.2 KB) means of tracking head position. The mechanical interface between the head band and the base of the ADL-1, however, resulted in a very restricted range of motion.

By comparison, electromagnetic head trackers such as the Polhemus Fastrack offered only modest accuracy, had a high latency, and most importantly, were effected by extraneous magnetic fields and ferromagnetic materials, so could not be used on board Spacelab. Optical sensors were expensive and the accuracy of acoustic sensors was limited by the ambient noise level, therefore were not chosen.

Since the ADL-1 was not supported by Sense8, it was necessary to develop a device driver for the head tracker so that it could interface with WTK. The code for the driver is given in Appendix A.

3.2.4 Eyephone Model I Head Mounted Display

A HMD was used instead of an off-head display due to the weight and volume constraints on experiments to be performed on Spacelab. The VPL Eyephone Model I is a stereo HMD. The vertical FOV is 58° and the binocular horizontal FOV is 90° with a 60° overlap between the left and right eye images [16]. It has two 360 x 240 monochrome LCDs with red, green, and blue filters overlaid to produce colour pixels. The display setup attaches to the head with a rubber mask and fabric straps.

The Eyephone I HMD was selected primarily because it was readily available. It also offered a wide effective FOV and had well characterized optics ([15], [16]). Wide FOV was needed as peripheral vision is important for the perception of self rotation [2].

The displays are viewed through "LEEP" Optics (manufactured by Pop Optics Labs, Waltham, MA) which magnified the LCD image to fill as much of the FOV of the eyes as possible. LEEP Optics does not feature an adjustable interpupillary distance (IPD), but instead uses a wide exit pupil to attempt to accommodate different IPDs. The FOV is largest with the eye in the primary position. When looking to the sides, vignetting occurs as the eye goes out of the exit pupil, preventing peripheral objects from being seen.

3.2.5 World Tool Kit C Library

The WTK Version 2.0 (manufactured by Sense8 Corp, Sausalito, CA) development system consists of a library of C functions for the design of 3-D graphics applications.

WTK features 24 bit colour, antialias filtering, wireframe rendering, flat shading, Gouraud shading, texture mapping, perspective correction, and either transparent or shaded textures. It accepts files from a variety of 3-D modelers and can be used in a dual board configuration to generate stereo images.

We opted for WTK because it facilitates communication with various kinds of input sensors and output devices, making it particularly well suited for virtual environment development. WTK supports texturing and could be run on multiple platforms allowing code to be easily ported should there be such a need.

3.3 Head Tracker Performance Issues

Figure 3-2 shows the design of the ADL-1, the various joints and joint angles, together with the base of the fixed frame (X,Y,Z). It was necessary to write a device driver to interface the ADL-1 head tracker with WTK. The following sections discuss some of the issues that arose while designing the device driver.

3.3.1 Small Joint Angle Approximation Errors

The ADL-1 can provide position and orientation information in several formats: cartesian coordinates and euler angles, cartesian orientation matrix, joint angle values, and raw data. The cartesian coordinates and euler angles format was chosen because conversion of this representation into the quaternion format used internally by WTK was easy, although there is one drawback to this format. The following approximations were made in calculating the euler angles:

$$roll = angle4$$
$$pitch = angle1 + angle2 + angle3$$
$$yaw = angle0 + angle5$$

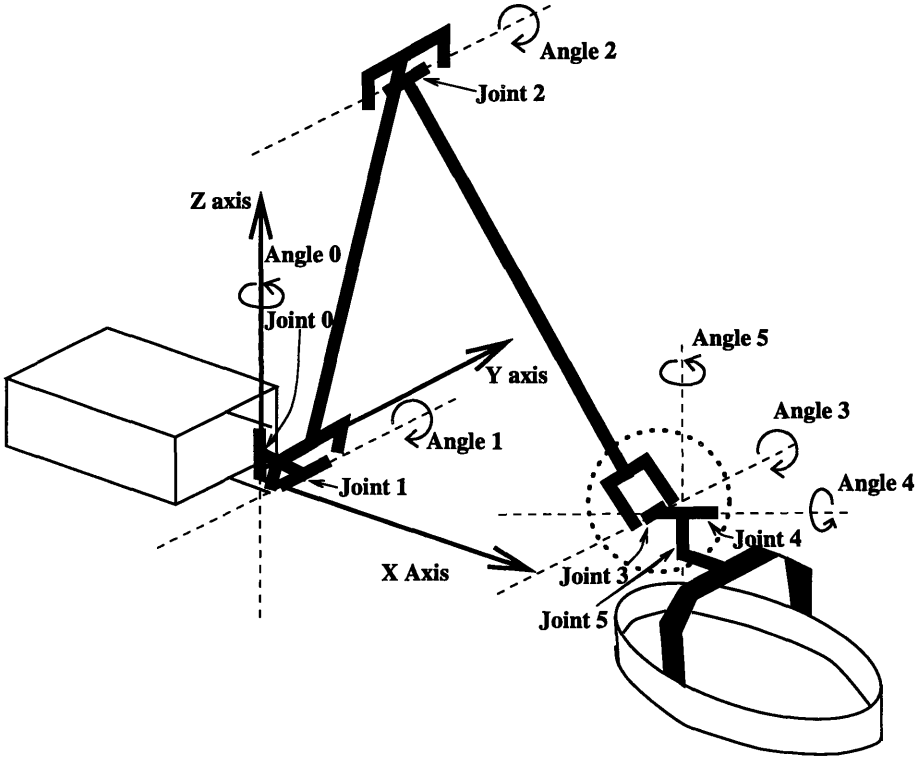

Figure 3-2: Design of the ADL-1 Head Tracker

As a result of the above approximations the euler angles were only accurate if the arm was rotated to lie along the X axis (see Fig 3-2). The further away the arm was from the X axis the worse the approximation. For example, if the user yawed his head by 90° and then pitched it, according to the approximation the pitch would be interpreted as a roll. To minimize such error, the subject was asked to follow the computer when using the head tracker so that the pitch and yaw angles were restricted to a maximum value of 35°.

Position and Orientation Information

The position vector was provided for Joint 3 (see Fig 3-2) instead of a point that represented the midpoint between the user's eyes. Joint 3 was approximately 10 inches away from the midpoint between the user's eyes. Orientation information corresponded to that of Joint 5. Thus, the position and orientation information was a better approximation to a point near the top of the user's head rather than to his eyepoint. In the experiment no correction was made to obtain the position and

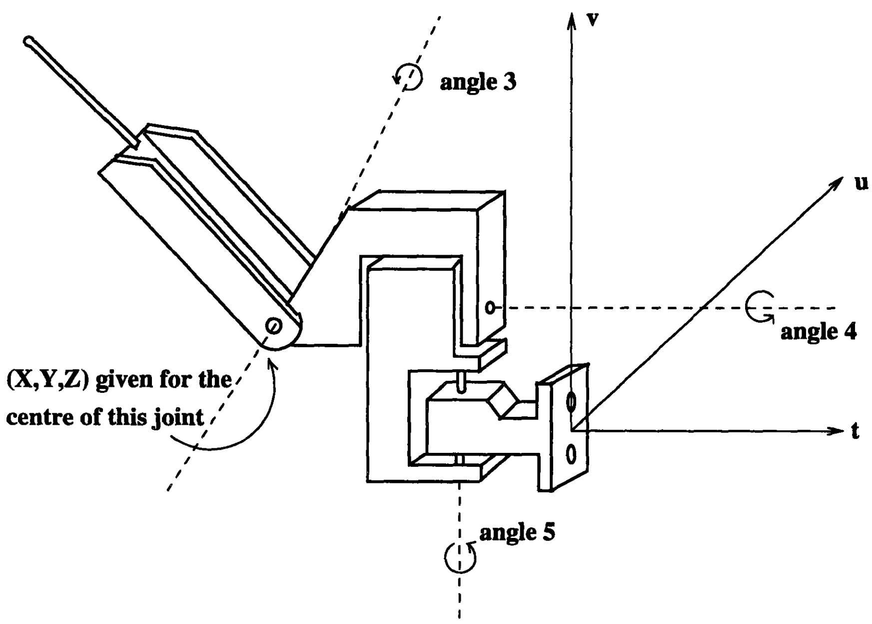

Figure 3-3: Detail of End Effector Joint

orientation information from the midpoint between the user's eyes. Calculating the correct position and orientation information from the joint angles would involve using a transformation matrix to map points from the (t,u,v) moving frame (see Fig 3-3) to the coordinates of the fixed frame (X,Y,Z). This transformation is computationally expensive and would increase the head tracker's lagtime if implemented in host computer. The possibility of adding an external micro-processor to do this calculation is being considered.

3.3.2 Relative Coordinates

WTK only accepted from its sensors relative coordinates which it then used to move whichever objects were attached to the sensor in the virtual world. If a sensor provided absolute coordinates, it was necessary to take the first difference in absolute coordinates to generate relative values. WTK then integrated the relative coordinates back to an absolute coordinate which was then used. During this process errors due to round-off, low sampling rate, etc., were also integrated and grew over time. The faster the sensor was moved the quicker the error grew. In our system the viewpoint was controlled by the head tracker. These errors resulted in a drift of the view seen by the subject from a particular head orientation.

When testing the system over several minutes it was found that the drift in the orientation of the viewpoint was easily detectable whereas drift in position was much harder to detect. In a study by Westheimer et al. (1976), it was found that on 75% of trials subjects could detect when a line was as little as 0.5° from the vertical. These tests were performed in an otherwise dark room and so presented a lower limit on the angular deviations humans can detect. Nonetheless, the test results indicate that humans have a high sensitivity for angular deviations in both vertical and horizontal lines. Aliasing increases our sensitivity to these deviations because a small change in the angle of a near horizontal or vertical line results in a pronounced difference in staircasing. When testing the system, errors in orientation due to drift were readily observable and distracting. In addition, as horizontal and vertical lines constitute the visual frame, errors in the orientation of them could alter the results of experiments studying the effects of visual frame on perceived self orientation.

Drift in Orientation

To overcome the drift in orientation it was necessary to write an update function for the head tracker that used the euler angles from the head tracker to directly update the viewpoint. The euler angles were first scaled and then rotated for them to correspond to the orientation of the viewpoint. The WTK function WTeuler_2q was then used to convert the euler angles to a quaternion representation. This was followed by WTviewpoint_setorientation to reorient the viewpoint. The relativising and reconstruction phases that introduced the drift were thus circumvented. This implementation maps the euler angles from the head tracker onto a specific initial viewpoint orientation. A general mapping onto any initial viewpoint has not been implemented, but this could be done by reading in the the initial viewpoint orientation and using these values to calculate the required mapping.

Drift in Position

As mentioned above, since the drift in position was hard to detect, the relative coordinates were calculated from the absolute values received from the ADL-1, and these were passed to WTviewpoint_translate to move the viewpoint position.

It was necessary to scale the cartesian coordinates received from the ADL-1 to virtual world units. The data received from the ADL-1 was in units of inches, and the virtual world was in units of decifeet (scale 10 units: 1 ft). Multiplying the values from the head tracker by 5/6 converted them to virtual world units.

3.3.3 Sampling Rate

The ADL-1 could operate up to a maximum of 115.2 KB. At the present time, WTK Version 2.0 only supports serial communications up to 19.2 KB, so the ADL-1 was consequently constrained to communicate at this rate.

The ADL-1 was operated in the data demand mode in which the ADL-1 only sent data over the serial port when it received a request for the data from the host. To request data, the host sent one byte, corresponding to a 'g' (ASCII 103), over the serial port. The ADL-1 responded to each request by sending six data records over the serial port corresponding to the cartesian coordinates and euler angles. Each data record was two bytes long, so a total of 12 bytes were needed to transfer the position and orientation information. A total of 13 bytes of serial communication were necessary each time data were required from the ADL-1. At 19.2 KB, this required 5.5 ms, which means a maximum of 184 data transfers per second were possible.

In order to calculate what the actual sampling rate was, it was necessary to understand the WTK event scheduling loop (Fig 3-4). The sensors were read and the scene rendered once per cycle. Thus the sampling rate of the head tracker was equal to the scene update rate. Since the experiments were conducted using rendering that was Gouraud shaded, texture mapped, and perspective corrected, the average update rate was approximately 18.1 updates per second, corresponding to 55 ms/update. Thus the ADL-1 was sampled at 18.1 Hz. This sampling rate could be achieved at

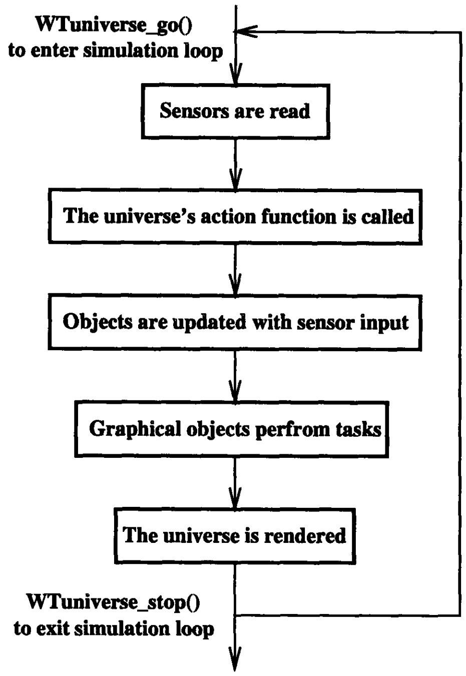

Figure 3-4: WTK event scheduling (adapted from [WTK Ref. Manual])

1.9 KB, so the ADL-1 was sampled at 1/10 its potential sampling rate of 19 KB.

At this sampling rate the latency of the ADL-1 (5.5 ms) did not add to the latency through the simulation loop. This was because the request for data was made just after the sensors' inputs were read, and the data were received from the head tracker before the sensors were reread.

3.4 Head Mounted Display Parameters

In order to maximize the immersiveness of the VES it was necessary to obtain an orthoscopic projection of the images in the HMD. The goal was to make the subject feel as if he was in a real room. WTK allows the parallax, aspect ratio, FOV, and convergence parameters of the viewpoint to be specified. Table 3.3 summarizes the values of these parameters used for the VRR experiment. The measurements made on the Eyephone I by Robinett and Rolland [16] were used in determining these settings. During the VRR experiment each subject was asked if the scene was "in focus". All the subjects said it was in focus so none of the parameters were varied for any part of the experiment for that reason. The following sections discuss how the parameters values were calculated.

Table 3.3: Viewpoint Parameters (Virtual World Scale, 10 unit: 1 foot)

Parameter	WTK command used	Assigned Value
Parallax	WTviewpoint_setparallax	2.034
Aspect Ratio	WTviewpoint_setaspect	0.81
View Angle	WTviewpoint_setviewangle	0.655
Convergence	WTvewpoint_setconvergence	-63

3.4.1 Parallax

Parallax is defined in WTK as the distance between the positions from which the right and left eye views are drawn in the 3D virtual world. This corresponds to the subject's IPD but has to be specified in virtual world units.

The IPDs among adults vary considerably, with 95% falling within the range from 49 to 75mm [18]. For this study, we set the parallax to 62mm, which is the average IPD. The result of using a fixed parallax setting was that the same scene in the HMD would appear to have different absolute sizes to subjects with different IPDs. To correct for this the IPD of each subject would have to be measured and the parallax adjusted accordingly. In the furnished room used in the VRR experiment, there were no objects in the virtual world within a meter of the subject's viewpoint and so stereopsis was not crucial for illiciting 3-D information. Relative motion, perspective, occlusion, shadows, and perspective were instead probably more important in creating a percept of depth. Thus adjustment of the parallax setting for each user was omitted. Robinett and Holloway [15] noted that the IPD of the UNC HMDs were often set at an average value of 62 mm as it was not practical to change the setting for each user.

3.4.2 Aspect Ratio

The aspect ratio is a vertical scale factor that is applied to the screen image. It can be used to correct for monitor or pixel distortion responsible for causing spherical objects to look flattened or square objects rectangular. To adjust the aspect ratio the casing of the HMD was removed to expose the LCDs. The furnished room was then displayed on the LCDs and the aspect ratio was varied until the image of the 7 ft x 7 ft front wall appeared square. An aspect ratio of 0.81 was needed to achieve this.

3.4.3 Field Of View

WTK allows the user to set the viewangle which corresponds to half the horizontal angular field of view. The viewangle was set using the vertical FOV instead of the horizontal FOV as the latter also depended on the convergence. Using the vertical FOV calculated by Robinett and Rolland [16], markers corresponding to a 58.4° FOV were placed on the ceiling and floor of the furnished room. The FOV was then adjusted until the markers matched the vertical edges of the display. This resulted in a viewangle setting of 0.655 radians, corresponding to a 75° horizontal viewangle.

3.4.4 Convergence

Convergence is defined by WTK as the horizontal offset in pixels that is applied to both the left and right eye images by subtracting from the left eye and adding to the right eye. When viewing in stereo it is necessary to adjust the convergence to overlay the right and left eye images. The greater the overlap between the left and right eye images the more distant the virtual image seems.

To set the convergence, markers were placed on the walls of the furnished room corresponding to a 75.3° horizontal FOV. The convergence setting was then changed to match these markers with the horizontal edges of the screen image. This resulted in a setting of -63. Since the optical distortion of the VPL was largest at the periphery of the lens, using an edge to edge definition of FOV resulted in objects in the centre not being orthoscopic. However the difference in apparent size was relatively small.

Chapter 4

Virtual Rotating Room Experiment

This chapter describes the virtual environment and the Virtual Rotating Room (VRR) experimental design.

4.1 Virtual Environment

4.1.1 Design of the Virtual Environment

3DStudio (version 2.0) was initially used to design the virtual environment (VE) as it supported texturing and could produce an output format (3DS) that could be imported into WTK. However, the process of exporting a 3DS file from 3DStudio and then importing it into WTK resulted in a model that contained more polygons than expected. By exporting the file from WTK in an ASCII file format called Neutral File Format (NFF), it was determined that some of the polygons were unnecessary. As having a low polygon count was important to achieve acceptable scene update rates, we opted to manually design the room to limit the polygon count.

The VE was designed by writing a NFF file for each of the objects in the room, and then using the programme wtk.c, provided by Sense8, to scale and position these objects in the room. Once all the objects were positioned a NFF file of the virtual

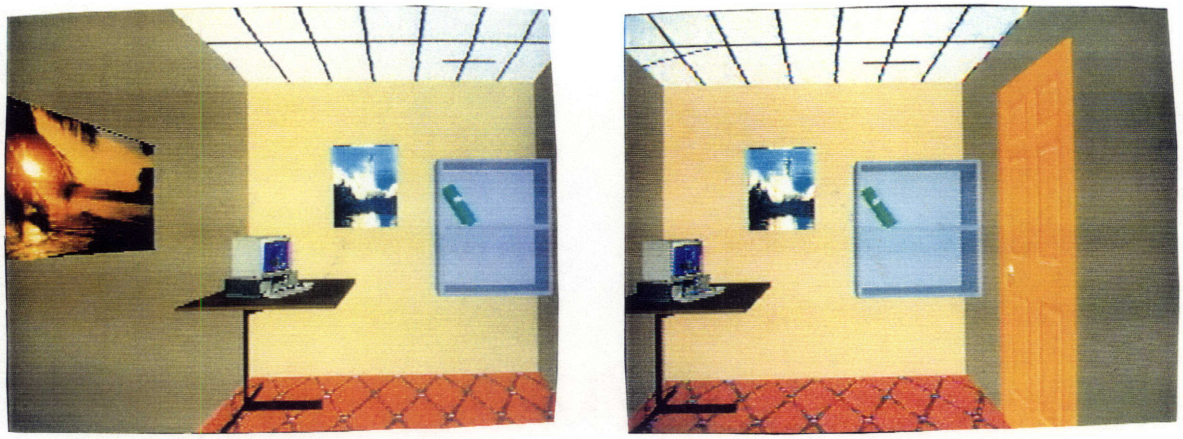

Figure 4-1: Right and Left Eye Views of Virtual Environment

universe was generated and used as the VE for the VRR experiments.

4.1.2 Description of Virtual Environment

Fig 4-1 shows the right and left eye images of the virtual environment. These pictures were taken from a TV and so do not exactly represent the images in the HMD. For example, compared to a TV, the HMD images are of a lower resolution and are vignetted.

The virtual room was cuboidal with a 7 ft x 7 ft front wall. The room was 14 ft in length with pale yellow walls, a red patterned floor, and a white tiled ceiling. The left wall had a wooden door, and the right wall a picture of a tropical beach at sunset. The wall in front of the user had a blue grey bookshelf, with a green covered book leaning against one of its sides. Hanging from the front wall is a picture of a space shuttle launch. There was also a desk with a computer on top of it. Thus the room contained many polarised objects and scenes that could provide information about which direction was up and which was down. The room was rolled about an axis going through the centre of the front wall. When the head tracker was not being used, the viewpoint was along the axis of rotation 9 ft away from the front wall.

The VE was an adaptation of the furnished room used by Howard and Childerson [7] for their tilting and rotating room experiments. Only textures available to us were used and some features in Howard's room were simplified to lower the polygon count. With more resources different textures could be used to more faithfully reproduce Howard's room. A rectangular door was used instead of an arched door. Curved objects such as the coffee cups, lamp, and sundae, were replaced with a book and a PC (taken from the models provided by WTK). The picture on the right wall was moved to the front wall. As a result of the restricted FOV of the HMD, we decided to move the subject's viewpoint further back, 9 ft away from the front wall. This viewpoint enabled most of the objects in the room to stay in view throughout the rotation of the room. As a result of this change, the room was lengthened to 14 ft instead of keeping the 7 ft dimension used by Howard. However the subject's head was kept along the axis of rotation for reasons mentioned earlier (Section 2.2).

The objects in the room were selected to provide a visual frame and visual polarity. The ceiling and floor patterns were selected to be easily distinguishable from each other. The leaning book provided a cognitive down cue. Many objects had prominent vertical and horizontal lines, such as the bookshelf, the desk, and the computer. The pictures of the sunset and the shuttle had a distinct horizon, and the computer was chosen because it provided a strongly mono-oriented object very familiar in the daily lives of our subjects.

The objects in the room serve as an example of the use of texturing to render complex objects. However during rotation the details in the textures "sparkled" due to aliasing. It was necessary to perform perspective correction to eliminate the distortion introduced when viewing them obliquely.

4.2 Virtual Rotating Room Experimental Design

The experiment was designed to evaluate the VES and study the importance of head orientation, head tracking, and point of regard for induced self tilt and self rotation.

As the room rotated, the subject was asked to describe his subjective sensation. The subject's response was then classified.

4.2.1 Stimulus

The furnished room described at the beginning of this chapter was used as the stimulus for the experiment. The viewpoint was positioned 9 ft away from the front wall. The furnished room was presented to the subject, rotating continuously at approximately 30°/sec about the roll axis for six complete revolutions. It was not possible to set the speed of rotation exactly because of WTK's variable scene update rate.

Preliminary studies were conducted using three rotation speeds, $15°/sec$, $30°/sec$, and $45°/sec$, to determine which was most effective at inducing vection. Both $30°/sec$ and $45°/sec$ appeared to be equally effective and more convincing than $15°/sec$. This result was in agreement with the recent study done by Zacker and Allison in which they found that the tumbling sensation in Howard's room increased when the rotation speed went up from $15°/sec$ to $30°/sec$. A rotation speed of $30°/sec$ was selected over $45°/sec$ because it provided smoother motion for a given scene update rate. Higher rotation rates were achieved by rotating the scene through larger angles at each scene update. Since the scene update rate remained constant regardless of the speed of rotation, the smaller the angle through which the scene was rotated the smoother the motion. The speed chosen was twice that used by Howard and Childerson.

4.2.2 Orientation of Subject

The independent variable in the experiments was the head position. The different head positions were erect, supine, and inverted. For the erect case, the effect of a second head movement/tracking instruction (head fixed/centre, head fixed/periphery, and head free/periphery) was studied. There were a total of five different treatments.

Figure 4-2: Subject in erect position

Erect

The subject was seated with the head tracker and HMD attached to the head (Fig 4-2). Although the head tracker was strapped to the head during the three erect test, only one of them actually utilized the head tracker. Of the two tests that did not utilize the head tracker, one required the subject to look at the bottom right hand corner of the shuttle picture which was along the axis of rotation, and the other required the subject to track the computer screen with his eyes. The angle of gaze to the extreme edge of the computer screen was 35° from the roll axis. For the test with the head tracker the subject was asked to keep the computer in the centre of their view at all times. In the erect position gravity acted perpendicularly to the axis of rotation, as a result the otolith and visual input were discordant.

By comparing the results of the erect tests to those obtained by Howard and Childerson, the success of the VES in inducing self tilt and self motion could be evaluated.

Figure 4-3: Subject in supine position

Supine

The subject was asked to lie down on his back and hold the HMD to his head (Fig 4-3). Thus the axis of rotation of the visual stimulus was parallel to gravity. The test was performed without head tracking with the subject following the computer around the room with his eyes. In the supine position gravity acted along the axis of rotation. Thus the orientation implied by the rotation of the visual field around the roll axis did not alter the implied orientation of gravity with respect to the head. It may be that tests conducted with the subject in the supine position provide a better model of the initial and adaptive trends found in spaceflight. This is because in micro-gravity the otolith signals are unfamiliar but do not conflict with the orientation of gravity implied by the visual stimulus.

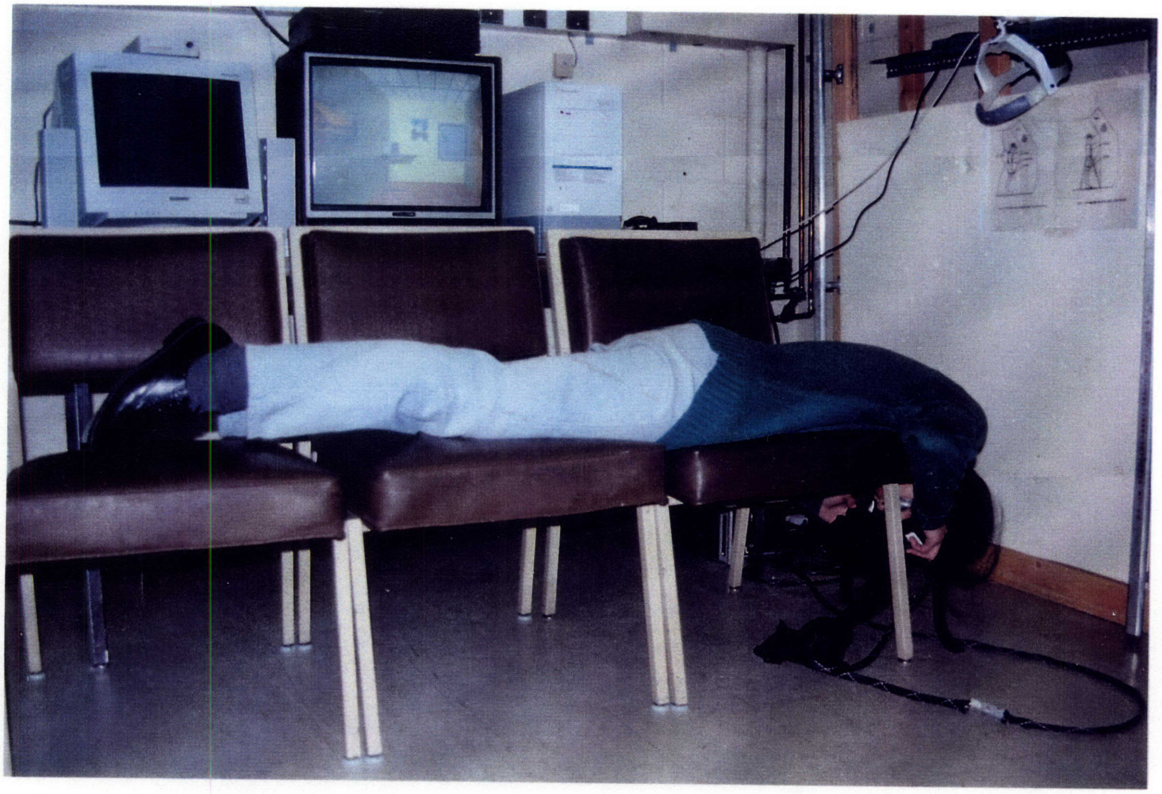

Figure 4-4: Subject with head inverted

Head inverted

This test was performed with the subject lying on their stomach and their head hanging upsidedown over the edge of the bench, holding the HMD to their eyes (Fig 4-4). The axis of rotation of the visual scene was perpendicular to gravity. The head tracker was not used, instead the subject was asked to track the computer with his eyes. In the inverted position, just as in the erect position, gravity acted perpendicularly to the axis of rotation, resulting in discordant otolith and visual information. This head inverted position shall be referred to as the *inverted* position.

4.2.3 Point of Regard

The point of regard is the point at which one is looking. Three different points of regard were tested in the erect position. In the first test, the subject was asked to look at the bottom right hand corner of the shuttle picture, i.e., along the axis of rotation. In the second, he was asked to follow a peripheral object around with his eyes. In the third, he was asked to use the head tracker to follow a peripheral object around the room.

The tests with and without the head tracker were performed to determine the importance of head tracking to induce illusions of self tilt and motion. If significantly more subjects experienced self rotation with the use of the head tracker than without, then the ability to track objects would be important. However if the results with the head tracker were less significant than without, then the test would have to be repeated in a real room to decouple the effects of head movement from the artifacts of head tracking (e.g. lag time, position approximation, etc.). Should head tracking prove unnecessary in inducing illudiond then the experimental setup would be simplified. In addition it would be possible to display the scenes to the subject at high frame rates to smoothe the motion of the scene. This can be achieved either by prerecording them on video or by precomputing them as an animation sequence.

4.2.4 Lighting

WTK allows the light intensity to be set within the range of 0.0-1.0. At 1.0 a non-textured polygon is rendered with the colour assigned to it, and at a lower intensity it is rendered with a darker shade of that colour. A texture whose shaded flag has been set is presented at full brightness when the light intensity is 1.0, and diminishes in brightness for lower values.

The ambient light level of the room was set at 0.46, and a directed light source was placed to coincide with the viewpoint aimed at the front wall. This light had an intensity setting of 0.2. This directed light was added to provide the shading necessary to discern the corners of the room and to better distinguish the objects within the room. This light was needed for both flat and gouraud shading. Studies ([5], [4]) have shown that shading influences the direction of perceived down. The light was directed along the axis of rotation of the room so that the shading in the room remained constant regardless of the roll angle of the scene.

4.2.5 Procedure

A total of twelve subjects were tested for the experiment. The subjects' ages spanned the range of 19 to 29 and they were all college students. A total of five tests were performed, three with the subject erect, one inverted, and the other supine. The tests were divided into two blocks, the erect tests, and the supine and inverted tests. The order of presentation was chosen to be well balanced and tests were randomly assigned to the subjects. While the tests within the two blocks were kept together, the order of presentation of the tests within the block was varied. Each session lasted approximately 25 minutes.

The order of presentation of the five tests for the 12 trials is shown in Table 4.1. The table is organized as follows: Head Position/Head Tracking/Point of Regard.

- I: Erect/Not Used/Centre
- II: Erect/Not Used/Periphery
- III: Erect/Used/Periphery
- A: Supine/Not Used/Periphery
- B: Inverted/Not Used/ Periphery

Table 4.1: Order of Presentation of the Tests

	First	Second	Third	Fourth	Fifth
1	I	II	III	A	B
2	I	III	II	B	A
3	II	III	I	A	B
4	II	I	III	B	A
5	III	I	II	A	B
6	III	II	I	B	A
7	A	B	I	II	III
8	B	A	I	III	II
9	A	B	II	III	I
10	B	A	II	I	III
11	A	B	III	I	II
12	B	A	III	II	I

Prior to the start of the tests, the subject was given an instruction sheet containing a description of the test (Appendix B). The subject was asked to describe their illusory sensations during the test. The instruction sheet suggested four categories of sensations borrowed from Howard and Childerson's experiment [7]. Additional questions were asked to help classify the sensations, and to informally determine if the time to the start of vection and the percentage saturation of vection were related to head orientation, head movement, and point of regard (Appendix B).

After the subject had read the instructions, he was seated and the head tracker and HMD were placed on his head. The subject was then given a tour of the virtual room with the head tracker being used. The tour consisted of a verbal introduction to the various objects in the room by the experimenter. This allowed him to familiarize himself with the room and become comfortable with the use of the head tracker. They were presented the room rotating clockwise at approximately $30^\circ/sec$ for about 2 minutes to help them better understand the meaning of vection and tilt. After the introduction the five tests were performed. Approximately 20 seconds were allowed between tests I-II-III. A couple of minutes was required to reposition the subject for tests A and B.

Chapter 5

Results

5.1 Performance Evaluation

The performance of the VES was first evaluated using the furnished room scene and then the benchmark scene (bench.nff) provided with WTK.

5.1.1 Rendering Performance and Update Rate Measurements

The furnished room had a total of 115 polygons of which 16 were texture mapped. The update rate was calculated by averaging the time required to complete 200 scene updates. This calculation was repeated three times and the results averaged. The performance in polygons per second was calculated by multiplying each of the three averages by 115 (the number of polygons) and averaging these numbers.

The time to update a single frame was obtained by measuring the time between successive calls to the universe action function. Figure 3-4 shows the default ordering of events in the simulation loop. The universe action function was called once each cycle through the simulation loop. Thus the time between successive calls to the universe function provided a measure of the scene update rate.

5.1.2 Performance Using Furnished Room

Table 5.1 presents the single board configuration performance, and Table 5.2 presents the dual board configuration performance of the VES.

Table 5.1: WTK Single Board Performance with Furnished Room(115 polygons)

Shading/Texturing	Performance polys/sec	Update Rate frames/sec
Wireframe	6572	57.1
Flat shaded, no texture	6279	54.6
Gouraud shaded, no texture	3369	29.3
Flat shaded, texture mapped	3350	29.1
Flat shaded, texture mapped, perspective corrected	3314	28.8
Flat shaded, texture mapped, anti-aliased	231	2
Flat shaded, texture mapped, perspective corrected, antialiased	192	1.7

Table 5.2: WTK Dual Board Performance with Furnished Room(115 polygons)

Shading/Texturing	Performance polys/sec	Update Rate frames/sec
Wireframe	6313	54.9
Flat shaded, no texture	2232	19.4
Gouraud shaded, no texture	2181	19
Flat shaded, texture mapped	2237	19.5
Flat shaded, texture mapped, perspective corrected	2104	18.3
Flat shaded, texture mapped, anti-aliased	216	1.9
Flat shaded, texture mapped, perspective corrected, antialiased	182	1.6

5.1.3 Performance Using WTK Benchmark Scene

The performance of the system was reevaluated using the WTK benchmark scene of a grid containing 256 textured polygons. The grid was loaded three times, as suggested by WTK, to give a total of 768 textured polygons. Table 5.3 and Table 5.4 provide the single and dual board configuration performances, respectively, of the VES using this scene.

Table 5.3: WTK Single Board Performance with WTK Benchmark Scene (768 polygons)

Shading/Texturing	Performance polys/sec	Update Rate frames/sec
Wireframe	18554	24.2
Flat shaded, no texture	14275	18.6
Gouraud shaded, no texture	7385	9.6
Flat shaded, texture mapped	7437	9.7
Flat shaded, texture mapped, perspective corrected	7282	9.5
Flat shaded, texture mapped, anti-aliased	2731	3.6
Flat shaded, texture mapped, perspective corrected, antialiased	2310	3

The performance measures using the furnished room were significantly lower than those using the benchmark scene. For example, in the single board setup with flat shaded rendering, the performance was 6279 polys/sec using the furnished room as opposed to 14275 polys/sec when using the benchmark scene. This discrepancy can be accounted for by the fact that the furnished room scene has a much lower polygon count than the benchmark scene provided by WTK. As a result of the higher scene update rate with the furnished room, its performance measures reflected the overhead paid each time the board has to clear the screen. Higher performance figures in terms of polygons per second can be achieved by using scenes with a large number of polygons that have a correspondingly low scene update rate. For this reason it is misleading to specify the performance of the VES in terms of polygons per second

Table 5.4: WTK Dual Board Performance with WTK Benchmark Scene (768 polygons)

Shading/Texturing	Performance polys/sec	Update Rate frames/sec
Wireframe	7259	9.5
Flat shaded, no texture	7085	9.2
Gouraud shaded, no texture	5875	7.7
Flat shaded, texture mapped	5890	7.7
Flat shaded, texture mapped, perspective corrected	5857	7.6
Flat shaded, texture mapped, anti-aliased	2723	3.6
Flat shaded, texture mapped, perspective corrected, antialiased	2310	3

alone.

WTK reported a performance of 17,200 polys/sec on a Pentium 66 MHz machine using an unspecified scene rendered using flat shading in the single board configuration. With the same type of rendering we achieved a performance of 14275 polys/sec with the benchmark scene (768 textured polygons) by using a Pentium 100 MHz in the single board configuration. This discrepancy could be explained if the scene used by WTK contained many more polygons than the benchmark scene.

Since an update rate of at least 15 - 20 frames/sec using texture mapped, perspective corrected rendering was desired for smooth motion, it was necessary to limit the number of polygons in the scene to about 100. For applications requiring higher frame rates than that provided by the WTK scene, the figures obtained using the furnished room provided a more realistic benchmark.

5.2 Variation in Update Rate

WTK does not provide a constant update rate, instead each frame takes as long as is necessary to complete rendering of the scene. These variations were noticeable when watching the furnished room rotate.

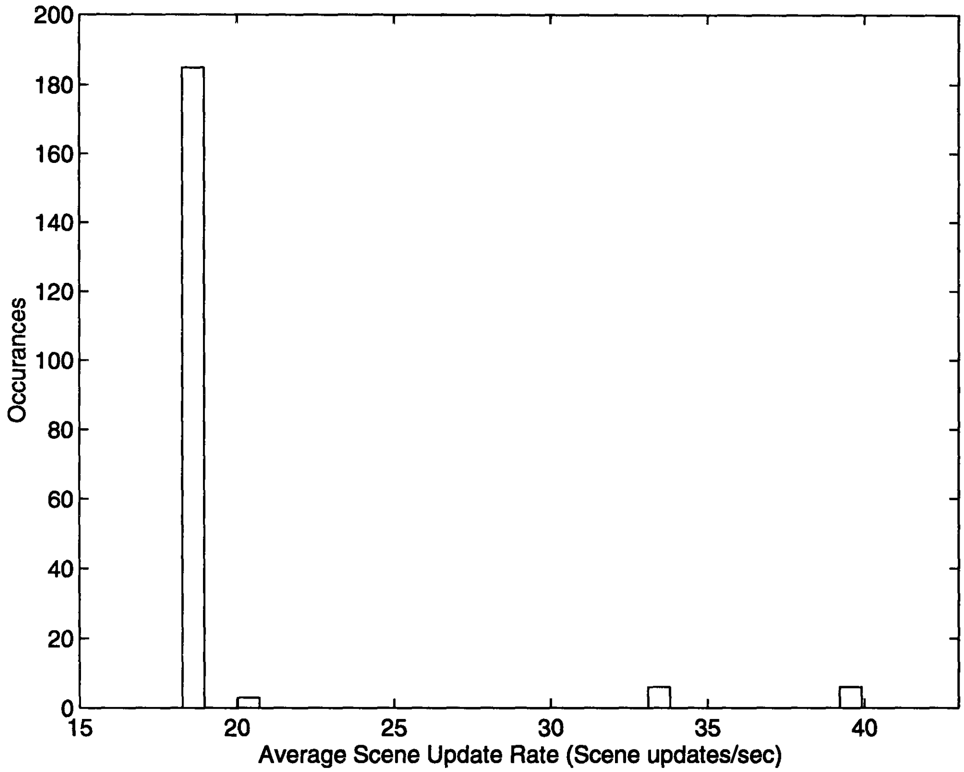

Figure 5-1: Histogram of average update rates using flat shaded, textured rendering.

5.2.1 Method

In order to determine the variation in the update rate, measurements of 400 successive updates were made. Some of the updates were performed too quickly to be timed reliably, so the four hundred measurements were averaged in groups of two to give 200 average update times. This method might have slightly underestimate the actual variation in update rate.

5.2.2 Variation in Update Rate Using Furnished Room

Figure 5-1 shows a histogram of 200 average update rates using the furnished room with flat shaded, texture mapped rendering. Figure 5-2 shows a histogram of 200 average update rates using the same room with flat shaded, texture mapped, perspective corrected rendering.

During informal experiments, we noted that variations in frame rate, i.e., pauses in rendering, resulted in dropouts of vection probably because they implied a small

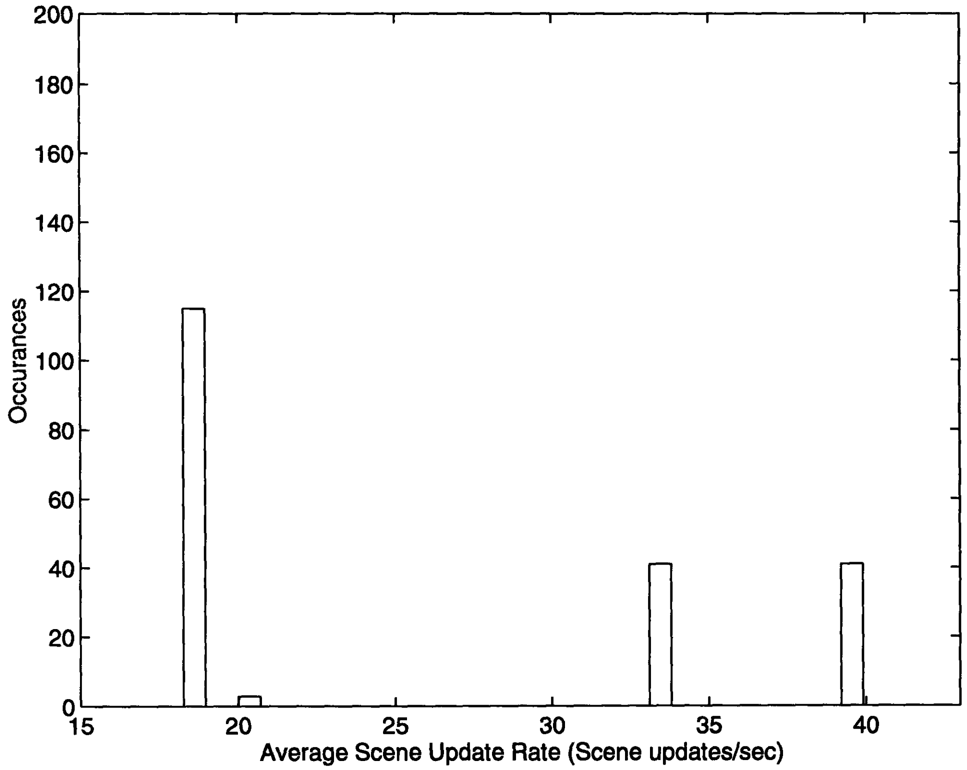

Figure 5-2: Histogram of average update rates using flat shaded, perspective corrected textured rendering.

but noticeable deceleration and the reacceleration of the scene. Thus these variations pose a problem for studying perceived self motion.

5.3 Tilting Room Experiment Results

The four categories used by Howard and Childerson were insufficient to accurately classify all the subjects' responses. Specifically, it was difficul to classify the responses from some subjects who experienced no self tilt or rotation with their bodies either gravitationally erect or supine. Similarly the response that they experienced full tumbling in a plane other than earth vertical was difficult to classify. No subjects reported constant self tilt (category 1 in [7]). Therefore the subjects' responses were retrospectively classified into one of the following six categories:

1. *No Vection Erect*: The subject felt as if he was either seated or standing watching the room rotate in front of him.

2. *No Vection Supine*: The subject felt as if he was lying down watching the room rotate above him.
3. *Alternating Tilt Erect*: The subject felt as if he was rotating about the earth horizontal axis up to some limiting angle, then felt upright, and then began to rotate again.
4. *Full Rotation in Earth Vertical Plane*: The subject experienced full tumbling through 360° in an earth vertical plane parallel to the front wall of the room.
5. *Full Rotation Tilted Plane*: The subject felt full tumbling through 360° in a plane other than the earth vertical. This includes full tumbling with body in the supine position.
6. *Other*: Any sensations that does not fall into the above five categories.

Three responses were classified in the "Other" category. One reported constant self tilt about the earth vertical axis, and the other two experienced alternating tilt with the body in the supine position. Table 5.5 summarizes the subjects' responses. None of the subjects ever experienced constant tilt about the roll axis.

The erect tests performed with the subjects looking at the centre and periphery generated the same overall results. Nine subjects (75%) experienced full tumbling through 360°, 2 subjects (16.67%) reported alternating tilt, and 1 subject (8.33%) experienced no illusion. For the test in which the head tracker was used, the subjects were able to keep the computer approximately in the centre of screen (the experimenter was able to watch their left eye view on a TV to verify this). For this test 6 subjects (50%) experienced no self tilt or self rotation, 4 subjects (33.3%) reported alternating tilt, and 2 subjects (16.67%) experienced complete tumbling – one in the erect position and the other one with his body tilted approximately 45° about the earth vertical axis towards the front wall.

In the supine position, out of the 5 subjects (41.67%) who experienced no vection, 4 felt as if they were supine and one as if he was erect. Out of 5 subjects (41.67%) who experienced full tumbling, four felt as if erect and one supine. The remaining

Test	No Vection Erect	No Vection Supine	Alt Tilt Erect	Full Rot in Earth Vertical	Full Rot Tilted	Other
Erect Centre	1 (8.3%)	0 (0%)	2 (16.7%)	9 (75%)	0 (0%)	0 (0%)
Erect Periphery	1 (8.3%)	0 (0%)	2 (16.7%)	9 (75%)	0 (0%)	0 (0%)
Erect Tracking	6 (50%)	0 (0%)	4 (33.3%)	1 (8.3%)	1 (8.3%)	0 (0%)
Supine	1 (8.3%)	4 (33.3%)	0 (0%)	4 (33.3%)	1 (8.3%)	2 (16.7%)
Head Inverted	2 (16.7%)	1 (8.3%)	3 (25%)	3 (25%)	2 (16.7%)	1 (8.3%)

Table 5.5: Virtual Tilting Room Results: Number of Subjects (Row Percentages)

two subjects (16.67%) in the supine position experienced alternating tilt with their bodies in the supine position looking up at the front wall. Both of these responses were classified as "Other".

The responses from the head inverted test were varied. Three subjects (25%) experienced no vection, of which 2 felt erect and one supine. Three subjects (25%) experienced alternating tilt with their bodies erect. Five subjects (41.67%) experienced full tumbling, of which 2 felt as if their bodies were tilted approximately 45° about the earth vertical axis away from the front wall, and the others felt erect. The remaining one subject also felt as if his body was tilted approximately 45° about the earth vertical axis away from the front wall, but did not experience any self-rotation. This response was classified in the "Other" category.

Considered together, the Table 5.5 shows a statistically significant relationship between condition and response categories (Pearson chi-square = 43, df = 20, $P < 0.002$).

Chapter 6

Discussion

6.1 Tilting Room Experiment

6.1.1 Comparison of the Five Tests

Both focusing on the centre of the screen and following an object near the periphery without the use of the head tracker gave the same overall results. They resulted in a compelling sense of rotation through 360° in 9 subjects (75%) in spite of the conflict between vestibular and visual input. This result confirmed the hypothesis that a VES can be used to induce vection. The fact that a larger percentage (75%) of subjects experienced full tumbling in the VES than in Howard and Childerson's real room (60%) is in part be due to the greater rotation speed, but it may also indicate that the VES can generate more compelling illusions. More research is needed to addresse this issue.

The result that 6 subjects (50%) experienced no illusion when using the head tracker and only subject (8.33%) experienced full tumbling was surprising. It was initially expected that the use of the head tracker would result in a more compelling illusion as a subject could select a single mono-oriented object and keep it continuously in view. This might resolve any 90° or 180° ambiguities in the rest of the scene. However the data did not support this view. Instead the results showed a low percentage of tumbling illusions when the tracker was in use. There are several factors which might have contributed to this result. First, the 55 ms head tracker lag time produced noticeable visual-vestibular discordance and might have destroyed the illusions of self rotation and tilt. Second, with the scene used, there were many mono-oriented objects continuously in view even when the head was fixed. Third, subjects might have been so preoccupied with tracking a single object and keeping it in the centre of the VPL display, that they paid less attention to other cues. Fourth, it is possible that the out-of-rotation-plane head movements created a "pseudo-Coriolis" effect (e.g., yaw when the head was pitched and pitch when the head was yawed) that augmented the cue conflict. Recently, Zacker and Allison studied the effects on head free versus head fixed conditions of induced self tilt and rotation in a real tumbling room. No consistent differences were found between conditions. The difference between using versus not using the head tracker found in the VRR experiment suggests that one or more of the first three factors was important.

It should be noted that one subject did not experience any self rotation in any of the tests except for the tracker, in which he felt full rotation with his body tilted. The subject was an architect and said that he used CAD software regularly so was accustomed to seeing rooms in all orientations on a screen, but the sensation when using the head tracker was new to him.

The result that only 33% experienced full tumbling in the supine position as compared with 75% in the erect position was surprising. We had expected the results to follow the trend noticed by Howard that visually induced self motion increased as the head was tilted away from the earth vertical axis. A possible explanation is that when the head is in the supine position the visual stimulus from the mono-oriented objects indicates that the down direction is along the earth horizontal axis, and the input from gravity receptors in the otolith organs indicates that the down direction is along the earth vertical axis. It may be that conflicting inputs that are perpendicular to each other are harder to resolve than when they are in the same plane.

The percentage of full tumbling (42%) with the head inverted (25% in an earth vertical plane, 17% in an off earth vertical plane) was less than with the head erect (75% in an earth vertical plane) even though the visual rotation axis was at the same

90° angle to gravity in both cases. The lower total percentage might be due to the unfamiliar and therefore more noticeable vestibular and haptic cues associated with the head inverted orientation. The head was below the body, resulting in fluid shift, and required muscular effort to hold the head and Eyephone in position.

Vection was apparently induced much more quickly in the erect position than in either the supine or inverted positions. Of the subjects that experienced no vection in the supine or inverted test, 80% of those in the supine test and a 100% of those in the inverted test performed the A-B block before the I-II-III block.

Finally, it was easier to induce illusions in subjects later in the session suggesting a learning effect. The elapsed time before a subject experienced self tilt and self motion decreased as the experiment progressed (informal observation).

6.2 Limitations of the VES

Following is a list of some of the problems encountered with various components of the system, and where appropriate the way in which they were dealt with.

6.2.1 World Tool Kit

Stereo Viewing

The work done by Robinett and Rolland [16] provides a computational model for the geometry of a HMD necessary to achieve constancy of the perceived size, shape, and relative positions of the simulated objects as the head moves around. In their paper they calculate the parameters specifically for the VPL Eyephone. Using these parameters together with the interpupillary distance of the subject allows one to generate orthoscopic images for the Eyephone.

WTK defines parallax (same as interpupillary distance) in units of the virtual world, so the parallax depends not only on the subject's interpupillary distance but also on the size of the virtual world.

WTK specifies convergence in terms of the number of pixels by which to shift the left and right eye images instead of a convergence distance. The correct image shift required to achieve an orthoscopic image is cumbersome to determine. Sense8 claims that this will be fixed in future releases with the introduction of asymmetric viewing capabilities.

Drift

WTK only accepts relative coordinates, so data from sensors that provide absolute coordinates need to relativised. These relative coordinates are then integrated by WTK together with sampling and quantization errors. The accumlation of error results in drift. When a sensor is used to control the viewpoint, the drift in the orientation is readily perceivable.

Maximum Baud Rates

WTK supports baud rates up to 19.2 KB. The ADL-1 head tracker could operate up to 115.2 KB, but had to be operated at 19.2 KB due to this constraint. However, as mentioned in Section 3.3.3, the sensor can only be sampled as fast as the scene update rate and thus may not fully utilize the 19.2 KB. With the furnished room at an update rate of 18.3 Hz, it was effectively communicating at 1.9 KB.

Variable Frame Rate

The frame rate varies dramatically depending on the the complexity of the scene being rendered. In addition the frame rate varies even if the scene is kept constant. Adapting the level of detail to stabilize the frame rate is a possible solution, provided it could be done without interfering with important visual cues.

6.2.2 SPEA i860 FIRE Graphics Boards

Binocular Colour Matching

A RGB to NTSC converter was required to use the FIRE boards with the Eyephone I. We used two Hormonic Research CV121 encoders to convert the RGB signals from the two FIRE boards into NTSC signals for the right and left eye LCDs. The colour component of the NTSC signals from the two converters were not exactly matched, resulting in the two LCD images having slightly different colours. However none of the subjects commented on this. Using the coverters also introduced some colour bleeding that was not present when viewing the FIRE board output directly on an RGB monitor.

PC Bus Speed

The SPEA boards connected to the ISA bus that operated at 8MHz. The bus limited the speed at which graphics information could be sent to and from the processor. The next generation of PCI bus boards will probably have much improved performance.

6.2.3 ADL-1 Head Tracker

Range of Operation

Due to the mechanical design of the joints, the range of motion was restricted. This limitation made it very difficult to perform erect, supine, and inverted tests with the head tracker on without reorienting the base of the ADL-1. We had mounted the base of the ADL-1 on a shelf for stability and calibration purposes. We were thus limited to performing only the erect tests with the use of the head tracker.

Joint Angle Measurement Noise

In our setup, the ADL-1 was used to control the viewpoint. Noise in the values provided by the ADL-1 resulted in a jittering of the scene even when the head tracker was completely stationary. The quantization errors and potentiometer noise in the head tracker were magnified by the display pixelization which resulted in perceptible angular and linear scene jitter.

Small Angle Approximation

The ADL-1 only provided accurate position and orientation information if the arm lay along the X axis. The further the arm was from the axis, the worse the approximation and the larger the error. The range of head movement was restricted to limit the error.

Origin of Moving Coordinate System

The position information provided by the ADL-1 corresponded to a joint in the arm that was approximately 10 in away from the midpoint of the users eyes (Fig 3-3). Thus when the viewpoint was controlled by the head tracker, the viewpoint better corresponded to a point near the top of the subject's head than to the midpoint between the subject's eyes. In order to change the point of reference, it is necessary to use the joint angles directly to transform points measured relative to the subject's head into a coordinate system measured with respect to the base.

This computation can be implemented in the host computer, either in an external processor or in the ADL-1. The calculation is computationally expensive and would slow down the scene update time if done on the host. Changing it within the ADL-1 would be the best solution but would require Shooting Star Technology to reprogramme the processor. Thus performing the calculation on an external processor provides a good alternative.

6.2.4 VPL Eyephone I

Optical Distortion

In the Eyephone, the LCD displays were viewed through LEEP optics. The optics caused a non-linear distortion of the image, making straight lines on the display appear curved in the virtual image.

Robinett and Rolland suggested a means of compensating for this distortion by mapping the image with the inverse of the distortion function. However, implementation of this idea would require the development of an optical distortion processor that could predistort the scene using the inverse distortion fuction.

Eye Relief

The Eyephone has an eye relief of approximately 29.4mm to accomodate spectacles. At this viewing distance, vignetting of the outermost edges of the LCD displays decreased the horizontal FOV.

Variability in the distance between the pupil and the screen among different subjects results in varying horizontal FOV in two ways. The first is the change in angle over which the virtual image is viewed, and the second is a change in the amount of vignettion of the edges of the LCDs. Thus the horizontal FOV varied between subjects.

Resolution

The Eyephone uses two 360 x 240 monochrome LCDs. In order to achieve colour, red, green, and blue filters were overlaid over the cells to divide the display array into three equally sized groups. A colour pixel consists of a triad of a red, green, and blue cell. Thus 86,400 monochrome cells result in 28,800 colour pixels, providing approximately 208 x 139 colour resolution. When this low resolution display is viewed through the LEEP optics, the individual pixels are clearly visible, therefore detracting from the quality of the images. Low resolution also restricts the amount of detail that can be displayed thus limiting the effectiveness of texturing.

Interpupillary Distance

There is no IPD adjustment for the Eyephone. Instead it uses LEEP optics that feature wide exit pupil lenses designed to accommodate a variety of interpupillary distances.

Comfort

The Eyephone I with harness weighs approximately 2 kg and may be uncomfortable to wear for extended periods. It is difficult to balance it properly on the user's head and ventilation tends to be poor.

Technical Support

VPL Research is defunct, so there is no technical support or repair service available for the Eyephone I. During the course of this research, the backlight on the left LCD display failed. Fixing the Eyephone I ourselves turned out to be an involving process. It was necessary to debug the system, obtain a replacement part (SONY 1-518-639-11), and install it to fix the Eyephone.

Chapter 7

Conclusion

The goal of this thesis was to build and evaluate a prototypic Virtual Environment System (VES) for research on human spatial orientation. The VES was also intended to be a reference system for the development of the NASA Virtual Environment Generator for the 1998 Spacelab mission called Neurolab. The VES was configured using a DOS personal computer running on an INTEL 100MHz Pentium processor, two SPEA i860 FIRE graphics accelerators, an Eyephone I Head Mounted Display (HMD), and an ADL-1 electromechanical head tracker. The software was developed using the World Tool Kit (WTK) Version 2.0 C library.

To evaluate the VES and study the influence of head orientation, head tracking, and point of regard on induced self tilt and motion, a Virtual Rotating Room (VRR) experiment was performed. This VRR experiment was based on a study by Howard and Childerson [7] using a real furnished rotating room. The virtual environment of a furnished room, designed to resemble Howard's room, contained many mono-oriented objects such as a computer, door, and desk.

The VES was able to achieve a performance of 2104 polygons/sec at 18.3 scene updates/sec with the furnished room scene (115 polygons including 16 textured polygons) when rendered using flat shading, texture mapping, and perspective correction. Perspective correction was necessary to correct the distortion introduced when viewing the textures obliquely. Antialiasing was not used because it decreased performance by a factor of ten. The performance was significantly lower than that quoted by the manufacturer of WTK, possibly because of the time penalty paid to refresh the screen at the update rate of the furnished room. However, high update rates were necessary for smooth motion. Some colour bleeding occured as a result of converting the video signal from RGB to NTSC, and the colour of the signals from the right and left eye converters were not exactly matched. When rotating the room, textures sparkled and WTK's non-constant scene update rate detracted from the smooth rotation. The use of the ADL-1 head tracker introduced several problems. Head tracker noise, magnified by the Eyephone's coarse pixelization, resulted in noticeable jitter. The ADL-1 could only be sampled at the scene update rate, so there was a 55ms lag between a head movement and the scene being updated. Small angle approximations made by the ADL-1 in generating the euler angles produced significant errors in certain head orientations. The error was controlled by limiting the range of head motion. Finally, a device driver for the ADL-1 was written to avoid drift in the viewpoint that occurred when providing relative coordinates to WTK to update the viewpoint. This was done by using the euler angles from the head tracker to orient the viewpoint.

In the VRR experiment, the furnished room was presented to the subject, rotating continuously about the roll axis at approximately $30°/sec$ for six complete revolutions. Five tests were performed: three with the subject erect, one supine, and one prone with the head inverted. For the inverted, supine, and one of the erect tests, the subject was asked to follow a peripheral object with their eyes as the room rotated. For the other two erect tests, the subject stared along the axis of rotation at the centre of the front wall in one, and used the head tracker to follow a peripheral object in the other. A total of 12 subjects were tested.

Both the erect tests that did not use the head tracker resulted in 75% of the subjects experiencing full tumbling. This result exceeded the 60% in Howard and Childerson's experiment, verifying the ability of the VES to produce illusory self tilt and motion. When using the head tracker, only 17% of the subjects felt full tumbling and 50% felt no illusion. The low percentage of full tumbling was attributed to conflict between visual and vestibular input due to head tracker lag, a restricted FOV, and the subject's preoccupation with the task of keeping the peripheral object in the centre of the display when using the head tracker.

In both the supine and inverted positions, the results were varied and 42% of the subjects experienced full tumbling (though the plane of rotation was sometimes tilted). The varied results necessitated introducing more categories to classify the subjects' sensations than mentioned by Howard [7]. It was surprising that fewer experienced full rotation in the supine position than in the erect because the gravitational and visual rotation axes were aligned when supine. Previous studies ([19], [6]) have shown a larger percentage of full tumbling in the supine position when rotating a dotted scene. In our experiment, the sensory conflicts between the otolith and haptic cues (aligned with gravity) and between gravity and the visual down cue (from the momo-oriented objects), might have reduced the illusion. The low percentage tumbling in the inverted test suggested that the unfamiliar haptic cues orthogonal to the axis of visual rotation augmented the conflict between the gravitation and visual cues hence decreased the illusion. A learning effect was noticed during the VRR experiment, indicating the importance of well balanced experiments and the use of trial runs to minimise learning effects during the experiment. The VRR experiment has confirmed the ability of the VES to induce illusory self rotation despite a significant reduction in normal human FOV and acuity. These results pave the way for the use of the NASA Virtual Environment Generator to study orientation illusions.

To study the influence of the visual down being orthogonal to gravity on vection in the supine position, a different experiment is needed. The experiment could consist of presenting a scene rotating about the earth vertical to a subject in the supine position. Two scenes are required, one with the visual down parallel to gravity, and the other orthogonal to gravity. In the VRR experiment, the head inverted test was conducted with the body prone. Repeating this test with the subject strapped to a rotating litter bed would enable the test to be performed with the entire body in the earth vertical plane. In addition, if the bed were motorized and could be made to oscillate, the "haunted swing" illusion could be recreated and studied. Finally studying the repeatability of responses of individual subjects is important, especially for the Neurolab project which will use repeat tests on a small population.

Appendix A

ADL-1 Head Tracker Device Driver

```
/*
 * Track.c: Device Driver for ADL-1
 *          Head tracker
 *
 * John de Souza
 * Man Vehicle Laboratory
 * Room 37-219, 77 Mass Av.,
 * Cambridge, MA 02139
 *
 * 2/15: Original
 * 5/21: Comments added
 */

#include <stdio.h>
#include <stdlib.h>
#include "mathlib.h"
#include "wt.h"

#include "mathlib.p"

/* 12 bytes for pos/orient record */
```

```
#define WTTRACK_NBYTES 12

/* constants for ADL-1 */
#define REQUEST 'g'
#define RESET 'x'
#define EULER 'c'

/* command - used to send char byte to tracker*/
static char *cmd;



/* structure within which to store
   raw data from the tracker.          */
typedef struct _WTtrack_rawdata {
  WTp3 p;
  WTp3 w;
} WTtrack_rawdata;

short firstbyte(int testbyte);

float bytetopos(char byte1, char byte2);

float bytetoang(char byte1, char byte2);


int WTtrack_open(WTsensor *sensor);

void WTtrack_close(WTsensor *sensor);

void WTtrack_update(WTsensor *sensor);


/*
 * Called to initialize the tracker
 */
```

```
int WTtrack_open(WTsensor *sensor)
{
        WTserial *serial;
        char track[WTTRACK_NBYTES];
        WTtrack_rawdata *raw;
        int checked, got_bytes;

        /* get pointer to serial object */
        serial = WTsensor_getserial(sensor);

        /* allocate raw data struct */
      WTsensor_setrawdata(sensor,(void *)xMalloc(sizeof(WTtrack_rawdata)));

        /* reset tracker */
        *cmd = RESET;
        WTserial_write(serial, cmd, 1);
        WTmsleep(100);

        /* set tracker output mode to euler angles */
        *cmd = EULER;
        WTserial_write(serial, cmd, 1);
        WTmsleep(100);

        /* request test record from tracker */
        *cmd = REQUEST;
        WTserial_write(serial, cmd, 1);
        WTmsleep(100);

        /* read test record from tracker */
        if ( WTserial_read(serial, track,
                                  WTTRACK_NBYTES, TRUE) == -1) {
                printf("Tracker not responding.\n");
                return FALSE;
        }

        /* request 1st tracker record */
```

```
    *cmd = REQUEST;
    WTserial_write(serial, cmd, 1);
    WTmsleep(100);

    /* read 1st byte */
    WTserial_read(serial, track, 1, FALSE);
    checked = 0;

    /* read bytes from the head tracker one byte
       at a time until first byte is found i.e. byte that
       has MSB set. */
    while ((!(firstbyte((int) track[0])))&&(checked<WTTRACK_NBYTES)){
                WTserial_read(serial, track, 1, FALSE);
                checked++;
        }
    got_bytes = 1;
    got_bytes = got_bytes + WTserial_read(serial, track+1, 11, FALSE);

    /* get pointers to raw data */
    raw = (WTtrack_rawdata *)WTsensor_getrawdata(sensor);

    /* put raw position data into raw data struct,
       this initialises raw */

    raw->p[X] = bytetopos(track[0], track[1]);
    raw->p[Y] = bytetopos(track[2], track[3]);
    raw->p[Z] = bytetopos(track[4], track[5]);
    raw->w[X] = bytetoang(track[6], track[7]);
    raw->w[Y] = bytetoang(track[8], track[9]);
    raw->w[Z] = bytetoang(track[10],track[11]);

    /* store raw data */
    WTsensor_setrawdata(sensor, raw);

    return TRUE;
}
```

```
/*
 * Free the tracker
 */

void WTtrack_close(WTsensor *sensor)
{
}


/*
 * read tracker and update viewpoint
 */

void WTtrack_update(WTsensor *sensor)
{
        WTserial        *serial;
        static char     track[WTTRACK_NBYTES];
        WTviewpoint     *view;
        WTtrack_rawdata *raw;
        WTpq            newview;
        static short    checked = 0;
     static short    got_bytes = 0;
        static short    count = 0;
        short           need, got;
        WTp3            last_abs_p;
        WTp3            p;

        /* get pointers to serial object */
        serial = WTsensor_getserial(sensor);

        WTserial_read(serial, track, 1, FALSE);


        /* test to see if byte sent by the tracker
```

```
   is the first byte of a data record
   i.e. if it has its MSB set. */

while ((!(firstbyte((int) track[0])))&&(checked<WTTRACK_NBYTES)){
                WTserial_read(serial, track, 1, FALSE);
                checked++;
        }

/* if first byte was not located then
   request a new data record from
   tracker */

if (checked == 12){
        printf("Could not locate first byte,requesting another data record.\n ");
        WTserial_write(serial, cmd,1);
        checked = 0;
        return;
}

/* found first byte,increment got_bytes, reset checked */
got_bytes = 1;
checked = 0;

/* read up to the needed # of bytes at the serial port */
need = WTTRACK_NBYTES − got_bytes ;

got = WTserial_read(serial, track+got_bytes, need, FALSE);
got_bytes += got;

if ( got!=need ) {
        count++;
        if ( count==5 ) {
                count = 0;
                printf("Data not received in five frames.\n");
                /* request a new record */
                WTserial_write(serial, cmd,1);
```

```
                /* reset byte counter to start over */
                got_bytes = 0;
            }
            return;
        }
        /* reset counters now that we have complete record */
        count = 0;
        got_bytes = 0;

        /* get pointers to raw data */
        raw = (WTtrack_rawdata *)WTsensor_getrawdata(sensor);

        /* Store prior absolute p, w, from the raw data storage*/
        last_abs_p[X] = raw->p[X];
        last_abs_p[Y] = raw->p[Y];
        last_abs_p[Z] = raw->p[Z];

        /* put raw position data into raw data struct */
        raw->p[X] = bytetopos(track[0], track[1]);
        raw->p[Y] = bytetopos(track[2], track[3]);
        raw->p[Z] = bytetopos(track[4], track[5]);
        raw->w[X] = bytetoang(track[6], track[7]);
        raw->w[Y] = bytetoang(track[8], track[9]);
        raw->w[Z] = bytetoang(track[10],track[11]);

        /* Calculate relative p, w */
        WTp3_subtract(raw->p,last_abs_p,p);

      /* scale position vector to virtual world units */
        newview.p[X] = -p[Y]*0.8333;
        newview.p[Y] = p[X]*0.8333;
        newview.p[Z] = p[Z]*0.8333;

      /* scale and rotate euler angles to match
        viewpoint base frame. convert from euler
          angle to quaternion representation */
```

```
        WTeuler_2q((2*(-raw->w[Y])+PI/2),(2*raw->w[Z]+PI),
                (2*raw->w[X]+PI),newview.q);

        /* update viewpoint using tracker data */
        view = WTuniverse_getviewpoint();
        WTviewpoint_translate(view,newview.p,WTFRAME_WORLD);
        WTviewpoint_setorientation(view,newview.q);

        /* store current absoute translation and rotation record*/
        WTsensor_setrawdata(sensor, raw);

        /* request next record */
      WTserial_write(serial, cmd, 1);
}



/*
 * check if byte has MSB set
 */
short firstbyte(int testbyte)
{
 if ((testbyte&128)!= 0) return(1);
 return(0);
}

/*
 * convert position record to inches
 */
float bytetopos(char byte1, char byte2)
{
 int sum;
 float position;

 sum = (((int) byte1)&127)*4 + (((int) byte2)&127)*512;
 if (sum>32768) sum=sum-65536;
 position = ((float)sum)/1000.0;
```

```
 return(position);
}

/*
 * convert orientation record to radians
 */
float bytetoang(char byte1, char byte2)
{
 int sum;
 float position;

 sum = (((int) byte1)&127)*4 + (((int) byte2)&127)*512;
 if (sum>32768) sum=sum−65536;
 position = (((float)sum)*PI)/(23040.0);
 return(position);
}
```

Appendix B

Virtual Rotating Room Experiment Instruction Sheet

Introduction

This experiment forms part of a study on the use of virtual environment systems for studying how humans process spatial orientation information. Developing a better understanding of how humans process such information in 1-G (on earth) will serve as a point of reference for interpreting the experiences of astronauts in micro-gravity. On earth gravity provides an omnipresent cue as to which direction is "down", but in space the lack of this cue has resulted in some striking visual reorientation illusions in which "floors", "ceilings", and "walls", exchange subjective identities. These illusions present a variety of human factors problems, and so better understanding them is of practical operational importance.

Experimental Setup

For this experiment a Head Mounted Display will be placed on your head. For part of the experiment you will also wear the head band of a Head Tracker on your head. The tests will be conducted with you either sitting or lying down on seats.

The Head Mounted Display looks like a diving mask with a counter weight attached to it. The diving mask houses two LCD TVs that will display the virtual environment. The head tracker is worn like a head band and provides the computer with information on which direction the subject is looking.

Once the apparatus is set up, please make sure of the following things

1. The apparatus feels comfortable. In particular make sure that the head tracker band is not too tight.
2. The scene is in focus i.e. you do not "see doubles". There are adjustments I can make to fix this.
3. Light is not entering the head set. When the TVs are off, it should be dark in the head set.
4. That one LCD does not seem significantly darker than the other. This probably indicates that the head set is not properly positioned on the head. Try moving it about and see if that helps.

Experimental Description

The experiment will consist of a series of tests conducted with you either sitting or lying down. For each test a virtual room will be displayed on the head set. The room will be made to rotate through a number of rotations. We are interested in your describing the sensation and seeing if it fits into one of the following categories:

1. Constant self-tilt. You feel as if your body is inclined at a constant angle. Please indicate the approximate angle with your hand, with the fingers pointing towards the direction of your head.
2. Alternating tilt and rotation. You feel as if you are rotating in the opposite direction to that of the room upto a certain limiting angle of tilt, then feel upright, and then begin tilting again.
3. Continuous tumbling through 360°. The subject feels as if the body is continuously rotating, head over heels, in a direction opposite to that of the room.
4. Looking at room from supine position. You feel as if you are looking either up or down (please indicate which) watching the room rotate about the earth vertical axis.

Please try to provide a continuous description of what you are feeling. Here are some things to comment on.

1. When do you begin to experience self tilt?
2. Does the sensation change over time? Does it depend on what you are looking at?
3. Does your body feel vertical, horizontal, or inclined at some angle in between (please indicate the angle).
4. Describe the speed of illusory self rotation. For example, do you feel you are rotating and the room is completely stationary (0%), or the room is rotating and you are stationary (100%), or something in between (e.g. 65%)?

Please feel free to ask for clarifications. Hope you have fun.

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