What Is Virtual Reality?
A Homebrew Introduction and Information Resource List
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(with thanks to the *many* people who contributed bits, bytes and words either directly to me or by posting to various electronic sources)

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2) ftp site sunee.uwaterloo.ca in the pub/vr/documents area as whatisvr.txt
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Introduction

This paper is divided into two parts. The first section is intended as an introduction to Virtual Reality (VR), primarily as background for development efforts. It is not meant to be The Definitive Treatise on VR. The reader is encouraged to search out other introductions and form your own opinions. The second section provides a large collection of places to search out more information on VR. It lists conventional books, on-line news groups, BBS, Ftp sites, local interest groups and commercial VR companies.

This is the second released version of this document. It contains a number of new information and lots of updated contact information in the second part. I don't know if I will be revising it again.

An excellent short treatment of the state of the art and a taxonomy of VR is a report on the US Government's National Science Foundation invitational workshop on Interactive Systems Program held March 23-24, 1992. It was published in the given in the ACM Siggraph publication "Computer Graphics", Vol. 26, #3, August 1992. The purpose of the workshop was to identify and recommend future research directions in the area of virtual environments. A longer exposition of this taxonomy can be found in the MIT Journal "Presence" Vol. 1 #2.

I. What is Virtual Reality

The term Virtual Reality (VR) is used by many different people with many meanings. There are some people to whom VR is a specific collection of technologies, that is a Head Mounted Display, Glove Input Device and Audio. Some other people stretch the term to include conventional books, movies or pure fantasy and imagination. The NSF taxonomy mentioned in the introduction can cover these as well. However, my personal preference, and for purposes of this paper, we restrict VR to computer mediated systems. The best definition of Virtual Reality I have seen to date comes from the book "The Silicon Mirage" (see section on VR Books):

"Virtual Reality is a way for humans to visualize, manipulate and interact with computers and extremely complex data"

The visualization part refers to the computer generating visual, auditory or other sensual outputs to the user of a world within the computer. This world may be a CAD model, a scientific simulation, or a view into a database. The user can interact with the world and directly manipulate objects within the world. Some worlds are animated by other processes, perhaps physical simulations, or simple animation scripts. Interaction with the virtual world, at least with near real time control of the viewpoint, in my opinion, is a critical test for a 'virtual reality'.

Some people object to the term "Virtual Reality", saying it is an oxymoron. Other terms that have been used are Synthetic Environments, Cyberspace, Artificial Reality, Simulator Technology, etc. VR is the most common and sexiest. It has caught the attention of the media.

The applications being developed for VR run a wide spectrum, from games to architectural and business planning. Many applications are worlds that are very similar to our own, like CAD or architectural modeling. Some applications provide ways of viewing from an advantageous perspective not possible with the real world, like scientific simulators and telepresense systems, air traffic control systems. Other applications are much different from anything we have ever directly experienced before. These latter applications may be the hardest, and most interesting systems. Visualizing the ebb and flow of the world's financial markets. Navigating a large corporate information base, etc.

I.1. Types of VR Systems

A major distinction of VR systems is the mode with which they interface to the user. This section describes some of the common modes used in VR systems.

I.1.1. Window on World Systems (WoW)

Some systems use a conventional computer monitor to display the visual world. This sometimes called Desktop VR or a Window on a World (WoW). This concept traces its lineage back through the entire history of computer graphics. In 1965, Ivan Sutherland laid out a research program for computer graphics in a paper called "The Ultimate Display" that has driven the field for the past nearly thirty years.

"One must look at a display screen," he said, "as a window through which one beholds a virtual world. The challenge to computer graphics is to make the picture in the window look real, sound real and the objects act real." [quoted from Computer Graphics V26#3]

I.1.2. Video Mapping

A variation of the WoW approach merges a video input of the user's silhouette with a 2D computer graphic. The user watches a monitor that shows his body's interaction with the world. Myron Kruger has been a champion of this form of VR since the late 60's. He has published two books on the subject: "Artificial Reality" and "Artificial Reality II". At least one commercial system uses this approach, the Mandala system. This system is based on a Commodore Amiga with some added hardware and software. A version of the Mandala is used by the cable TV channel Nickelodeon for a game show (Nick Arcade) to put the contestants into what appears to be a large video game.

I.1.3. Immersive Systems

The ultimate VR systems completely immerse the user’s personal viewpoint inside the virtual world. These "immersive" VR systems are often equipped with a Head Mounted Display (HMD). This is a helmet or a face mask that holds the visual and auditory displays. The helmet may be free ranging, tethered, or it might be attached to some sort of a boom armature.

A nice variation of the immersive systems use multiple large projection displays to create a ’Cave’ or room in which the viewer(s) stand. An early implementation was called "The Closet Cathedral" for the ability to create the impression of an immense environment. within a small physical space. The Holodeck used in the television series "Star Trek: The Next Generation" is afar term extrapolation of this technology.

I.1.4. Telepresence

Telepresence is a variation on visualizing complete computer generated worlds. This a technology links remote sensors in the real world with the senses of a human operator. The remote sensors might be located on a robot, or they might be on the ends of WALDO like tools. Fire fighters use remotely operated vehicles to handle some dangerous conditions. Surgeons are using very small instruments on cables to do surgery without cutting a major hole in their patients. The instruments have a small video camera at the business end. Robots equipped with telepresence systems have already changed the way deep sea and volcanic exploration is done. NASA plans to use telerobotics for space exploration. There is currently a joint US/Russian project researching telepresence for space rover exploration.

I.1.5. Mixed Reality

Merging the Telepresence and Virtual Reality systems gives the Mixed Reality or Seamless Simulation systems. Here the computer generated inputs are merged with telepresence inputs and/or the users view of the real world. A surgeon’s view of a brain surgery is overlaid with images from earlier CAT scans and real-time ultrasound. A fighter pilot sees computer generated maps and data displays inside his fancy helmet visor or on cockpit displays.

I.1.6. Fish Tank Virtual Reality

The phrase "fish tank virtual reality" was used to describe a Canadian VR system reported in the 1993 InterCHI proceedings. It combines a stereoscopic monitor display using LCD Shutter glasses with a mechanical head tracker. The resulting system is superior to simple stereo-WoW systems due to the motion parallax effects introduced by the head tracker. (see INTERCHI ’93 Conference Proceedings, ACM Press/Addison Wesley , ISBN 0-201-58884-6)

I.2. VR Hardware

There are a number of specialized types of hardware devices that have been developed or used for Virtual Reality applications.

I.2.1. Image Generators

One of the most time consuming tasks in a VR system is the generation of the images. Fast computer graphics opens a very large range of applications aside from VR, so there has been a market demand for hardware acceleration for a long while. There are currently a number of vendors selling image generator cards for PC level machines, many of these are based on the Intel i860 processor. These cards range in price from about $2000 up to $6 or $10,000. Silicon Graphics Inc. has made a very profitable business of producing graphics workstations. SGI boxes are some of the most common processors found in VR laboratories and high end systems. SGI boxes range in price from under $10,000 to over $100,000. The simulator market has produced several companies that build special purpose computers designed expressly for real time image generation. These computers often cost several hundreds of thousands of dollars.

I.2.2. Manipulation and Control Devices

One key element for interaction with a virtual world, is a means of tracking the position of a real world object, such as a head or hand. There are numerous methods for position tracking and control. Ideally a technology should provide 3 measures for position(X, Y, Z) and 3 measures of orientation (roll, pitch, yaw). One of the biggest problem for position tracking is latency, or the time required to make the measurements and preprocess them before input to the simulation engine.

The simplest control hardware is a conventional mouse, trackball or joystick. While these are two dimensional devices, creative programming can use them for 6D controls. There are a number of 3 and 6 dimensional mice/trackball/joystick devices being introduced to the market at this time. These add some extra buttons and wheels that are used to control not just the XY translation of a cursor, but its Z dimension and rotations in all three directions. The Global Devices 6D Controller is one such 6D joystick It looks like a racket ball mounted on a short stick. You can pull and twist the ball in addition to the left/right & forward/back of a normal joystick. Other 3D and 6D mice, joystick and force balls are available from Logitech, Mouse System Corp. among others.

One common VR device is the instrumented glove. The use of a glove to manipulate objects in a computer is covered by a basic patent in the USA. Such a glove is outfitted with sensors on the fingers as well as an overall position/orientation tracker. There are a number of different types of sensors that can be used. VPL (holders of the patent) made several DataGloves, mostly using fiber optic sensors for finger bends and magnetic trackers for overall position. Mattel manufactured the PowerGlove for use with the Nintendo game system, for a short time. This device is easily adapted to interface to a personal computer. It provides some limited hand location and finger position data using strain gauges for finger bends and ultrasonic position sensors. The gloves are getting rare, but some can still be found at Toys R' Us and other discount stores. Anthony Clifton recently posted this suggestion for a" very good resource for PowerGloves etc.: small children. A friend's son had gotten a glove a couple years ago and almost NEVER used it, so I bought it off the kid. Remember children like money more than toys they never use."

The concept of an instrumented glove has been extended to other body parts. Full body suits with position and bend sensors have been used for capturing motion for character animation, control of music synthesizers, etc. in addition to VR applications.

I.2.3. Position Tracking

Mechanical armatures can be used to provide fast and very accurate tracking. Such armatures may look like a desk lamp (for basic position/orientation) or they may be highly complex exoskeletons (for more detailed positions). The drawbacks of mechanical sensors are the encumbrance of the device and its restrictions on motion. Exos Systems builds one such exoskeleton for hand control. It also provides force feedback. Shooting Star system makes a low cost armature system for head tracking. Fake Space Labs and LEEP Systems make much more expensive and elaborate armature systems for use with their display systems.

Ultrasonic sensors can be used to track position and orientation. A set of emitters and receivers are used with a known relationship between the emitters and between the receivers. The emitters are pulsed in sequence and the time lag to each receiver is measured. Triangulation gives the position. Drawbacks to ultrasonics are low resolution, long lag times and interference from echoes and other noises in the environment. Logitech and Transition State are two companies that provide ultrasonic tracking systems.

Magnetic trackers use sets of coils that are pulsed to produce magnetic fields. The magnetic sensors determine the strength and angles of the fields. Limitations of these trackers are a high latency for the measurement and processing, range limitations, and interference from ferrous materials within the fields. However, magnetic trackers seem to be one of the preferred methods. The two primary companies selling magnetic trackers are Polhemus and Ascension.

Optical position tracking systems have been developed. One method uses a ceiling grid LEDs and a head mounted camera. The LEDs are pulsed in sequence and the cameras image is processed to detect the flashes. Two problems with this method are limited space (grid size) and lack of full motion (rotations). Another optical method uses a number of video cameras to capture simultaneous images that are correlated by high speed computers to track objects. Processing time (and cost of fast computers) is a major limiting factor here. One company selling an optical tracker is Origin Instruments.

Inertial trackers have been developed that are small and accurate enough for VR use. However, these devices generally only provide rotational measurements. They are also not accurate for slow position changes.

I.2.4. Stereo Vision

Stereo vision is often included in a VR system. This is accomplished by creating two different images of the world, one for each eye. The images are computed with the viewpoints offset by the equivalent distance between the eyes. There are a large number of technologies for presenting these two images. The images can be placed side-by-side and the viewer asked (or assisted) to cross their eyes. The images can be projected through differently polarized filters, with corresponding filters placed in front of the eyes. Anaglyph images user red/blue glasses to provide a crude (no color) stereovision.

The two images can be displayed sequentially on a conventional monitor or projection display. Liquid Crystal shutter glasses are then used to shut off alternate eyes in synchronization with the display. When the brain receives the images in rapid enough succession, it fuses the images into a single scene and perceives depth. A fairly high display swapping rate (min. 60hz) is required to avoid perceived flicker. A number of companies made low cost LC shutter glasses for use with TVs (Sega, Nintendo, Toshiba, etc.). There are circuits and code for hooking these up to a computer available on many of the On-line systems, BBSs and Internet FTP sites mentioned later. However, locating the glasses themselves is getting difficult as none are still being made or sold for their original use. Stereographics sells a very nice commercial LC shutter system called CrystalEyes.

Another alternative method for creating stereo imagery on a computer is to use one of several split screen methods. These divide the monitor into two parts and display left and right images at the same time. One method places the images side by side and conventionally oriented. It may not use the full screen or may otherwise alter the normal display aspect ratio. A special hood viewer is placed against the monitor which helps the position the eyes correctly and may contain a divider so each eye e sees only its own image. Most of these hoods, such as the one for the V5 of Rend386, use fresnel lenses to enhance the viewing. An alternative split screen method orients the images so the top of each points out the side of the monitor. A special hood containing mirrors is used to correctly orient the images. A very nice low cost (under $200) unit of this type is the Cyberscope available from Simsalabim.

I.2.5. Head Mounted Display (HMD)

One hardware device closely associated with VR is the Head Mounted Device (HMD). These use some sort of helmet or goggles to place small video displays in front of each eye, with special optics to focus and stretch the perceived field of view. Most HMDs use two displays and can provide stereoscopic imaging. Others use a single larger display to provide higher resolution, but without the stereoscopic vision.

Most lower cost HMDs ($3000-10,000 range) use LCD displays, while others use small CRTs, such as those found in camcorders. The more expensive HMDs use special CRTs mounted along side the head or optical fibers to pipe the images from non-head mounted displays. ($60,000 and up). A HMD requires a position tracker in addition to the helmet. Alternatively, the display can be mounted on an armature for support and tracking (a Boom display).

I.2.6. Health Hazards from Stereoscopic Displays

There was an article supplement with CyberEdge Journal issue #17 entitled "What's Wrong with your Head Mounted Display". It is a summary report on the findings of a study done by the Edinburgh Virtual Environment Lab, Dept. of Psychology, Univ. of Edinburgh on the eye strain effects of stereoscopic Head Mounted Displays. There have been a number of anecdotal reports of stress with HMDs and other stereoscopic displays, but few, if any, good clinical studies. This study was done very carefully and the results are a cause for some concern.

The basic test was to put 20 young adults on a stationary bicycle and let them cycle around a virtual rural road setting using a HMD (VPL LX EyePhone and a second HMD LEEP optic equipped system). After 10 minutes of light exercise, the subjects were tested...

"The results were alarming: measures of distance vision , binocular fusion and convergence displayed clear signs of binocular stress in a significant number of the subjects. Over half the subjects also reported symptoms of such stress, such as blurred vision."

The article goes on to describe the primary reason for the stress - the difference between the image focal depth and the disparity. Normally, the when your eyes look at a close object they focus (accommodate) close and also rotate inward (converge). When they accommodate on a far object, the eyes also diverge. However, a stereoscopic display does not change the either the effective focal plane (set by the optics) and the disparity depth. The eyes strain to decouple the signals.

The article discusses some potential solutions, but notes that most of them (dynamic focal/disparity) are difficult to implement. It mentions monoscopic HMDs only to say that while they would seem to avoid the problems, they were not tested. The article does not discuss non-HMD stereoscopic devices at all, but I would extrapolate that they should show some similar problems. The full article is available from CyberEdge Journal for a small fee.

There has been a fair bit of discussion ongoing in the sci.virtual-worlds newsgroup (check the Sept./Oct. 93 archives) about this and some other studies. One contributor, Dipl.-Ing. Olaf H. Kelle, University of Wuppertal, Germany, reported only 10% of his users showing eye strain. His system is setup with a focal depth of 3m which seems to be a better, more comfortable viewing distance. Others have noted that long duration monitor use often leads to the user staring or not blinking. It is common for VDT users to be cautioned to look away from the screen occasionally to adjust their focal depth and to blink. Another contributor, John Nagle provided the following list of other potential problems with HMDs: electrical safety, Falling/tripping over real world objects, simulator sickness (disorientation due to conflicting motion signals from eyes and inner ear), Eye Strain, Induced post-HMD accidents ("some flight simulators some flight simulators, usually those for military fighter aircraft, it’s been found necessary to forbid simulator users to fly or drive for a period of time after flying the simulator".).

I.3. Levels of VR Hardware Systems

The following defines a number of levels of VR hardware systems. These are not hard levels, especially towards the more advanced systems.

I.3.1. Entry VR (EVR)

The ’Entry Level’ VR system takes a stock personal computer or workstation and implements a WoW system. The system may be based on an IBM clone (MS-DOS/Windows) machine or an Apple Macintosh, or perhaps a Commodore Amiga. The DOS type machines (IBM PC clones) are the most prevalent. There are Mac based systems, but few very fast rendering ones. Whatever the base computer it includes a graphic display, a 2D input device like a mouse, trackball or joystick, the keyboard, hard disk & memory.

I.3.2. Basic VR (BVR)

The next step up from an EVR system adds some basic interaction and display enhancements. Such enhancements would include a stereographic viewer (LCD Shutter glasses) and a input/control device such as the Mattel PowerGlove and/or a multidimensional (3D or 6D) mouse or joystick.

I.3.3. Advanced VR (AVR)

The next step up the VR technology ladder is to add a rendering accelerator and/or frame buffer and possibly other parallel processors for input handling, etc. The simplest enhancement in this area is a faster display card. For the PC class machines, there are a number of new fast VGA and SVGA accelerator cards. These can make a dramatic improvement in the rendering performance of a desktop VR system. Other more sophisticated image processors based on the Texas Instruments TI34020 or Intel i860 processor can make even more dramatic improvements in rendering capabilities. The i860 in particular is in many of the high end professional systems. The Silicon Graphics Reality Engine uses a number of i860 processors in addition to the usual SGI workstation hardware to achieve stunning levels of realism in real time animation.

An AVR system might also add a sound card to provide mono, stereo or true 3D audio output. Some sound cards also provide voice recognition. This would be an excellent additional input device for VR applications.

I.3.4. Immersion VR (IVR)

An Immersion VR system adds some type of immersive display system: a HMD, a Boom, or multiple large projection type displays (Cave).

An IVR system might also add some form of tactile, haptic and touch feedback interaction mechanisms. The area of Touch or Force Feedback (known collectively as Haptics) is a very new research arena.

I.3.5. Cockpit Simulators

A common variation on VR is to use a Cockpit or Cab compartment to enclose the user. The virtual world is viewed through some sort of view screen and is usually either projected imagery or a conventional monitor. The cockpit simulation is very well known in aircraft simulators, with a history dating back to the early Link Flight Trainers (1929?). The cockpit is often mounted on a motion platform that can give the illusion of a much larger range of motion. Cabs are also used in driving simulators for ships, trucks, tanks and 'battle mechs'. The latter are fictional walking robotic devices (i.e. the Star Wars films). The BattleTech location based entertainment (LBE) centers use this type of system.

I.3.6. SIMNET, Defense Simulation Internet

One of the biggest VR projects is the Defense Simulation Internet. This project is a standardization being pushed by the USA Defense Department to enable diverse simulators to be interconnected into a vast network. It is an outgrowth of the Defense Advanced Research Projects Administration (DARPA) SIMNET project of the later 1980s. SIMNET was/is a collection of tank simulators (Cab type) that are networked together to allow unit tactical training. Simulators in Germany can operate in the same virtual world as simulators in the USA, partaking of the same battle exercise.

The basic Distributed Interactive Simulation (DIS) protocol has been defined by the Orlando Institute for Simulation & Training. It is the basis for the next generation of SIMNET, the Defense Simulation Internet (DSI). (love those acronyms!) An accessible, if somewhat dark, treatment of SIMNET and DSI can be found in the premier issue of WIRED magazine (January 1993) entitled "War is Virtual Hell" by Bruce Sterling.

The basic DIS protocol has been adopted as a standard for communication between distributed simulations by the IEEE. Basic information on DIS and SIMNET, including a C library to support the communication protocol is available via FTP from the Internet site taurus.cs.nps.navy.mil (pub/warbreaker/NPS_DIS...). Other contact points for DIS include:

Danette Haworth Institute for Simulation & Training 12424 Research Parkway, Suite 300 Orlando, Florida 32826 (407)658-5000

Defense Modeling and Simulation Office (DMSO) has an Internet site to support Advanced Distributed Simulation Technology (ADST). The IP address is 137.249.32.17
Administrative Contact: Kevin Mullally 407.382.4580, Technical Contact: Brad Mohning 408.473.4962

I.4. Available VR Software Systems

There are currently quite a number of different efforts to develop VR technology. Each of these projects have different goals and approaches to the overall VR technology. Large and small University labs have projects underway (UNC, Cornell, U.Rochester, etc.). ARPA , NIST, National Science Foundation and other branches of the US Government are investing heavily in VR and other simulation technologies. There are industry supported laboratories too, like the Human Interface Technologies Laboratory (HITL) in Seattle and the Japanese NTT project. Many existing and startup companies are also building and selling world building tools (Autodesk, IBM', Sense8, VREAM).

There are two major categories for the available VR software: toolkits and authoring systems. Toolkits are programming libraries, generally for C or C++ that provide a set of functions with which a skilled programmer can create VR applications. Authoring systems are complete programs with graphical interfaces for creating worlds without resorting to detailed programming. These usually include some sort of scripting language in which to describe complex actions, so they are not really non-programming, just much simpler programming. The programming libraries are generally more flexible and have faster renders than the authoring systems, but you must be a very skilled programmer to use them. (Note to developers: if i fail to mention your system below, please let me know and I will try to remember to include it when, and if, i update this document again)

I.4.1. Freeware VR Programs

At the low end of the VR spectrum are the freeware products and garage or home-brew VR hackers (like me!). There are currently a few fast rendering programs that have been released with source code and no charge. These programs are generally copyrighted freeware, which means that the original creators retain the copyright and commercial use is restricted. They are not polished commercial programs, and are often written by students. However, these programs exist to give people a very low cost entry into the VR world.

Rend386 is one such freeware library and world player written for 386/486 DOS systems. It was written by Dave Stampe and Bernie Roehl at the University of Waterloo, Canada. It creates images at a resolution of 320x200x256 and supports various extra devices such as the Mattel PowerGlove, LC shutter glasses, Split Screen stereo viewers etc. Rend386 is provided both as a complete world player and as a C source code. It does not provide a full authoring environment for world and object building. Dave and Bernie co-authored the book "Virtual Reality Creations" with John Eagan. It serves as the primary user documentation for Rend386 Version 5. There is also an electronic mail list for Rend386. Rend386 is available on the via ftp (sunee.uwaterloo.ca), CompuServe's CyberForum, and also from a large number of BBSes.

ACK3D is a freeware C programming library developed by Lary Meyer that provides a fast 'raycasting' renderer for PC systems. This technique restricts the user motion somewhat, but allows textures to be drawn at very impressive rates. The technique gained a fair bit of exposure with the

Wolfenstein 3D series of shareware games. ACK3D can be found on the CompuServe Gamer's forum and also via ftp from ftp.u.washington.edu in the pub/virtual-worlds/cheap-vr area.

Gossamer, a freeware VR package for the Apple Macintosh system, written by Jon Blossom. Source code has not been released yet, but Jon has released a demo and a Think C library. Jon is currently working on a new version that will support file compatibility with Rend386 V5 and a more extensive user program. The current version is available on via ftp from ftp.apple.com in the directory pub/VR, and also on CompuServe's CyberForum.

Multiverse is a freeware UNIX based client/server system written by Robert Grant. It is a multi-user, non-immersive, X-Windows based Virtual Reality system, primarily focused on entertainment/research. It includes capabilities for setting up multi-person worlds and a client/server type world simulation over a local or long haul network. Multiverse source and binaries for several flavors of UNIX are available via anonymous ftp from medg.lcs.mit.edu in the directory pub/multiverse

The MRToolkit is a programming library for UNIX systems that is available at no cost from the University of Alberta, but the licensing agreement stipulates no commercial products may be made with it.

VEOS is another programming toolkit that provides a basis for VR development on networked UNIX machines. Source code is available from the Human Interface Technology Lab (HITL) at University of Washington. (ftp.u.washington.edu)

I.4.2. VR Programs for under $200

There are a number of commercial VR programs that sell for under $200. Many computer games that can be considered in this category, such as Wolfenstein 3D, but these are often closed systems that do not allow much customizing or world building by the user.

Virtual Reality Studio (aka VR Studio, VRS) is a very low cost VR authoring system that does allow the user to define their own virtual worlds. This program is also known as "3D Construction Kit" in Europe. The program has a fairly nice graphical interface and includes a simple scripting language. It is available for about $100 from Domark for PC and Amiga systems. Worlds created with the program can be freely distributed with a player program. There are a quite number of these worlds available from the BBSes, and other sources. Compuserve's Cyberforum has several in its libraries, like the company provided demo VRSDMO.ZIP (VRS.TXT gives a solution to the demo game). Version 2 of VR Studio was released in early 1993. It has many new features including a much enhanced scripting language and editor, but also an annoying number of bugs. The developers of VRS (Dimension International) are working hard to correct these.

Another entrant into the low cost market is the Lepton VR Data Modeling Toolkit. This package is a collection of C programming libraries for real-time 3d data modeling on DOS systems. Version 1.0 is scheduled to be released in Fal1993 and will cost approximately $150.

For the Macintosh market there are the Qd3d, 3dPane, and SmartPane C++ libraries from ViviStar Consulting ($192 for full package). These provide a full suite of 3D graphics functions for popular Macintosh C++ compilers as well as Think C 6.0.

I.4.3. VR Packages under $1000

The next level of VR System is those costing between two hundred and one thousand dollars. There are some very excellent professional packages appearing in this price range in the last year. Most of these systems do not require any specialized hardware beyond the basic computer system.

VREAM is a complete VR authoring package for MS-DOS systems for about $795 from VREAM, Inc.. It provides a nice GUI environment for creation of objects and worlds, as well as a fairly powerful scripting language. VREAM supports a very wide variety of input and output devices, including HMDs. Two versions of the runtime system are available at a much lower cost to provide only the playback ability. The lower cost runtime (under $50) will work only with standard VGA display and mouse/joystick. The advanced runtime system supports more devices.

Virtus Walkthrough, from Virtus Corp., is available for both Mac and Windows systems. It provides a nice 3D modeling package and the ability to interactively control the viewpoint within the created worlds. However, it does not allow for interaction with the objects. The latest version Walkthrough Pro supports texture maps, including QuickTime movies.

Sense 8 has announced a $795 programming library for Windows called World Tool Kit for Windows. This will be released late in 1993 as a DLL for Windows systems. It will work directly with standard SVGA displays and show worlds with texture mapping either within a window or allow full screen display. The programming library will support DDE so a virtual world can be controlled from a spreadsheet, database or other program.

I.4.4. VR Software for over $1000

The heavy duty professional VR software packages begin at about $1000 and can go up dramatically. The hardware required to run these systems varies. Most support a DOS environment with add in rendering cards like the i860 based SPEA Fireboard. A few work on SGI and other workstation system. There are also other packages available that run on vendor specific hardware configurations. The really high end packages require extremely expensive hardware "Image Generators" such as those used in flight simulators.

The Sense8 World Tool Kit (WTK) is probably the most widely used product of this type. It runs on a wide variety of platforms from i860 assisted PCs to high end SGI boxes. It has won several awards for excellence.

The Autodesk Cyberspace Development kit is another product in this range. It is a C++ library for MSDOS systems using the Metaware HighC/C++ compiler and Pharlap DOS 32bit extender. It supports VESA displays as well as several rendering accelerator boards (SPEA Fireboard, FVS Sapphire, Division's dView). I used this system for a few months and found it requires a strong background in C++ and a rendering accelerator card. VESA speeds were about 4 frames per second.

Straylight Corp. makes a package called PhotoVR that uses special rendering boards (Intel ActionMedia cards) to provide excellent texture mapped walkthrough environments.

Dimension International's Superscape VRT3 is a very powerful authoring system for virtual worlds. It provides both a graphical environment for object and world creation and a lower level C library.

Division Ltd. sells a programming environment for VR called dVS. This package runs on SGI systems, IBM RS/6000 workstations and a proprietary Division workstation. They also sell a complete world authoring and simulation program similar to VREAM and VRT3 called dVise.

Lightscape is a radiosity rendering package for creating realistically shaded walkthroughs from Lightscape Graphics Software. This product runs on high end workstations and is aimed primarily at architects and lighting designers.

There have been a number of other packages introduced recently for professional VR development. I do not have full information on all of them and suggest the interested reader follow up by reading either the AI Expert Special Report on Virtual Reality or perhaps by purchasing Sophistech's VR Sourcebook.

I.5. Aspects of A VR Program

Just what is required of a VR program? The basic parts of the system can be broken down into an Input Processor, a Simulation Processor, a Rendering Process, and a World Database. All these parts must consider the time required for processing. Every delay in response time degrades the feeling of 'presence' and reality of the simulation.

I.5.1. Input Processes

The Input Processes of a VR program control the devices used to input information to the computer. There are a wide variety of possible input devices: keyboard, mouse, trackball, joystick, 3D & 6D position trackers (glove, wand, head tracker, body suit, etc.). A networked VR system would add inputs received from net. A voice recognition system is also a good augmentation for VR, especially if the user's hands are being used for other tasks. Generally, the input processing of a VR system is kept simple. The object is to get the coordinate data to the rest of the system with minimal lag time. Some position sensor systems add some filtering and data smoothing processing. Some glove systems add gesture recognition. This processing step examines the glove inputs and determines when a specific gesture has been made. Thus it can provide a higher level of input to the simulation.

I.5.2. Simulation Process

The core of a VR program is the simulation system. This is the process that knows about the objects and the various inputs. It handles the interactions, the scripted object actions, simulations of physical laws (real or imaginary) and determines the world status. This simulation is basically a discrete process that is iterated once for each time step or frame. A networked VR application may have multiple simulations running on different machines, each with a different time step. Coordination of these can be a complex task.

It is the simulation engine that takes the user inputs along with any tasks programmed into the world such as collision detection, scripts, etc. and determines the actions that will take place in the virtual world.

I.5.3. Rendering Processes

The Rendering Processes of a VR program are those that create the sensations that are output to the user. A network VR program would also output data to other network processes. There would be separate rendering processes for visual, auditory, haptic (touch/force), and other sensory systems. Each renderer would take a description of the world state from the simulation process or derive it directly from the World Database for each time step.

I.5.3.1. Visual Renderer

The visual renderer is the most common process and it has a long history from the world of computer graphics and animation. The reader is encouraged to become familiar with various aspects of this technology.

The major consideration of a graphic renderer for VR applications is the frame generation rate. It is necessary to create a new frame every 1/20 of a second or faster. 20 frames per second (fps) is roughly the minimum rate at which the human brain will merge a stream of still images and perceive a smooth animation. 24fps is the standard rate for film, 25fps is PAL TV, 30fps is NTSC TV. 60fps is Showscan film rate. This requirement eliminates a number of rendering techniques such as raytracing and radiosity. These techniques can generate very realistic images but often take hours to generate single frames.

Visual renderers for VR use other methods such as a ’painter’s algorithm’, a Z-Buffer, or other Scanline oriented algorithm. There are many areas of visual rendering that have been augmented with specialized hardware. The Painter’s algorithm is favored by many low end VR systems since it is relatively fast, easy to implement and light on memory resources. However, it has many visibility problems. For a discussion of this and other rendering algorithms, see one of the computer graphics reference books listed in a later section.

The visual rendering process is often referred to as a rendering pipeline. This refers to the series of sub-processes that are invoked to create each frame. A sample rendering pipeline starts with a description of the world, the objects, lighting and camera (eye) location in world space. A first step would be eliminate all objects that are not visible by the camera. This can be quickly done by clipping the object bounding box or sphere against the viewing pyramid of the camera. Then the remaining objects have their geometry’s transformed into the eye coordinate system (eye point at origin). Then the hidden surface algorithm and actual pixel rendering is done.

The pixel rendering is also known as the ’lighting’ or ’shading’ algorithm. There are a number of different methods that are possible depending on the realism and calculation speed available. The simplest method is called flat shading and simply fills the entire area with the same color. The next step up provides some variation in color across a single surface. Beyond that is the possibility of smooth shading across surface boundaries, adding highlights, reflections, etc.

An effective short cut for visual rendering is the use of "texture" or "image" maps. These are pictures that are mapped onto objects in the virtual world. Instead of calculating lighting and shading for the object, the renderer determines which part of the texture map is visible at each visible point of the object. The resulting image appears to have significantly more detail than is otherwise possible. Some VR systems have special ’billboard’ objects that always face towards the user. By mapping a series of different images onto the billboard, the user can get the appearance of moving around the object.

I need to correct my earlier statement that radiosity cannot be used for VR systems due to the time requirements. There have recently been at least two radiosity renderers announced for walkthrough type systems - Lightscape from Lightscape Graphics Software of Canada and Real Light from Atma Systems of Italy. These packages compute the radiosity lighting in a long time consuming process before hand. The user can interactively control the camera view but cannot interact with the world. An executable demo of the Atma product is available for SGI systems from ftp.iunet.it (192.106.1.6) in the directory ftp/vendor/Atma.

I.5.3.2. Auditory Rendering

A VR system is greatly enhanced by the inclusion of an audio component. This may produce mono, stereo or 3D audio. The latter is a fairly difficult proposition. It is not enough to do stereo-pan effects as the mind tends to locate these sounds inside the head. Research into 3D audio has shown that there are many aspects of our head and ear shape that effect the recognition of 3D sounds. It is possible to apply a rather complex mathematical function (called a Head Related Transfer Function or HRTF) to a sound to produce this effect. The HRTF is a very personal function that depends on the individual's ear shape, etc. However, there has been significant success in creating generalized HRTFs that work for most people and most audio placement. There remains a number of problems, such as the 'cone of confusion' wherein sounds behind the head are perceived to be in front of the head.

Sound has also been suggested as a means to convey other information, such as surface roughness. Dragging your virtual hand over sand would sound different than dragging it through gravel.

I.5.3.3. Haptic Rendering

Haptics is the generation of touch and force feedback information. This area is a very new science and there is much to be learned. There have been very few studies done on the rendering of true touch sense (such as liquid, fur, etc.). Almost all systems to date have focused on force feedback and kinesthetic senses. These systems can provide good clues to the body regarding the touch sense, but are considered distinct from it. Many of the haptic systems thus far have been exo-skeletons that can be used for position sensing as well as providing resistance to movement or active force application.

I.5.3.4. Other Senses

The sense of balance and motion can be served to a fair degree in a VR system by a motion platform. These are used in flight simulators and some theaters to provide some motion cues that the mind integrates with other cues to perceive motion. It is not necessary to recreate the entire motion perfectly to fool the mind into a willing suspension of disbelief.

The sense of temperature has seen some technology developments. There exist very small electrical heat pumps that can produce the sensation of heat and cold in a localized area. These system are fairly expensive.

Other senses such as taste, smell, pheromone, etc. are beyond our ability to render rapidly and effectively. Sometimes, we just don't know enough about the functioning of these other senses.

I.6. World Space

The virtual world itself needs to be defined in a 'world space'. By its nature as a computer simulation, this world is necessarily limited. The computer must put a numeric value on the locations of each point of each object within the world. Usually these 'coordinates' are expressed in Cartesian dimensions of X, Y, and Z (length, height, depth). It is possible to use alternative coordinate systems such as spherical but Cartesian coordinates are the norm for almost all applications. Conversions between coordinate systems are fairly simple (if time consuming).

I.6.1. World Coordinates

A major limitation on the world space is the type of numbers used for the coordinates. Some worlds use floating point coordinates. This allows a very large range of numbers to be specified, with some precision lost on large numbers. Other systems used fixed point coordinates, which provides uniform precision on a more limited range of values. The choice of fixed versus floating point is often based on speed as well as the desire for a uniform coordinate field.

I.6.2. A World Divided: Separation of Environments

One method of dealing with the limitations on the world coordinate space is to divide a virtual world up into multiple worlds and provide a means of transiting between the worlds. This allows fewer objects to be computed both for scripts and for rendering. There should be multiple stages (aka rooms, areas, zones, worlds, multiverses, etc.) and a way to move between them (Portals).

I.7. World Database

The storage of information on objects and the world is a major part of the design of a VR system. The primary things that are stored in the World Database (or World Description Files) are the objects that inhabit the world, scripts that describe actions of those objects or the user (things that happen to the user), lighting, program controls, and hardware device support.

I.7.1. Storage Methods

There are a number of different ways the world information may be stored: a single file, a collection of files, or a database. The multiple file method is one of the more common approaches for VR development packages. Each object has one or more files (geometry, scripts, etc.) and there is some overall 'world' file that causes the other files to be loaded. Some systems also include a configuration file that defines the hardware interface connections.

Sometimes the entire database is loaded during program startup, other systems only read the currently needed files. A real database system helps tremendously with the latter approach. An Object Oriented Database would be a great fit for a VR system, but I am not aware of any projects currently using one.

The data files are most often stored as ASCII (human readable) text files. However, in many systems these are replaced by binary computer files. Some systems have all the world information compiled directly into the application.

I.7.2. Objects

Objects in the virtual world can have geometry, hierarchy, scripts, and other attributes. The capabilities of objects has a tremendous impact on the structure and design of the system. In order to retain flexibility, a list of named attribute/values pairs is often used. Thus attributes can be added to the system without requiring changes to the object data structures.

These attribute lists would be addressable by name (i.e. cube.mass => mass of the cube object). They may be a scalar, vector, or expression value. They may be addressable from within the scripts of their object. They might be accessible from scripts in other objects.

I.7.2.1. Position/Orientable

An object is positionable and orientable. That is, it has a location and orientation in space. Most objects can have these attributes modified by applying translation and rotation operations. These operations are often implemented using methods from vector and matrix algebra.

I.7.2.2. Hierarchy

An object may be part of an object part HIERARCHY with a parent, sibling, and child objects. Such an object would inherit the transformations applied to it's parent object and pass these on to it's siblings and children. Hierarchies are used to create jointed figures such as robots and animals. They can also be used to model other things like the sun, Äplanets and moons in a solar system.

I.7.2.3. Bounding Volume

Additionally, an object should include a BOUNDING VOLUME. The simplest bounding volume is the Bounding Sphere, specified by a center and radius. Another simple alternative is the Bounding Cube. This data can be used for rapid object culling during rendering and trigger analysis. Objects whose bounding volume is completely outside the viewing area need not be transformed or considered further during rendering. Collision detection with bounding spheres is very rapid. It could be used alone, or as a method for culling objects before more rigorous collision detection algorithms are applied.

I.7.3. Object Geometry

The modeling of object shape and geometry is a large and diverse field. Some approaches seek to very carefully model the exact geometry of real world objects. Other methods seek to create simplified representations. Most VR systems sacrifice detail and exactness for simplicity for the sake of rendering speed.

The simplest objects are single dimensional points. Next come the two dimensional vectors. Many CAD systems create and exchange data as 2D views. This information is not very useful for VR systems, except for display on a 2D surface within the virtual world. There are some programs that can reconstruct a 3D model of an object, given a number of 2D views.

The sections below discuss a number of common geometric modeling methods. The choice of method used is closely tied to the rendering process used. Some renderers can handle multiple types of models, but most use only one, especially for VR use. The modeling complexity is generally inversely proportional to the rendering speed. As the model gets more complex and detailed, the frame rate drops.

I.7.3.1. 3D PolyLines & PolyPoints

The simplest 3D objects are known as PolyPoints and PolyLines. A PolyPoint is simply a collection of points in space. A Polyline is a set of vectors that form a continuous line.

I.7.3.2. Polygons

The most common form of objects used in VR systems are based on flat polygons. A polygon is a planar, closed multi-sided figure. They maybe convex or concave, but some systems require convex polygons. The use of polygons often gives objects a faceted look. This can be offset by more advanced rendering techniques such as the use of smooth shading and texture mapping.

Some systems use simple triangles or quadrilaterals instead of more general polygons. This can simplify the rendering process, as all surfaces have a known shape. However, it can also increase the number of surfaces that need to be rendered.

Polygon Mesh Format (aka Vertex Join Set) is a useful form of polygonal object. For each object in a Mesh, there is a common pool of Points that are referenced by the polygons for that object. Transforming these shared points reduces the calculations needed to render the object. A point at the edge of a cube is only processed once, rather once for each of the three edge/polygons that reference it. The PLG format used by REND386 is an example of a Polygonal Mesh, as is the BYU format used by the 'ancient' MOVIE.BYU program.)

. The geometry format can support precomputed polygon and vertex normals. Both Polygons and vertices should be allowed a color attribute. Different renderers may use or ignore these and possibly more advanced surface characteristics. Precomputed polygon normals are very helpful for backface polygon removal. Vertices may also have texture coordinates assigned to support texture or other image mapping techniques.

I.7.3.3. Primitives

Some systems provide only Primitive Objects, such as cubes, cones, and spheres. Sometimes, these objects can be slightly deformed by the modeling package to provide more interesting objects.

I.7.3.4. Solid Modeling & Boolean Operations

Solid Modeling (aka Computer Solid Geometry, CSG) is one form of geometric modeling that uses primitive objects. It extends the concept by allowing various addition, subtraction, Boolean and other operations between these primitives. This can be very useful in modeling objects when you are concerned with doing physical calculations, such as center of mass, etc. However, this method does incur some significant calculations and is not very useful for VR applications. It is possible to convert a CSG model into polygons. Various complexity polygonal models (# polygons) could be made from a single high resolution ''metaobject" of a CSG type.

I.7.3.5. Curves & Patches

Another advanced form of geometric modeling is the use of curves and curved surfaces (aka patches). These can be very effective in representing complex shapes, like the curved surface of an automobile, ship or beer bottle. However, there is significant calculation involved in determining the surface location at each pixel, thus curve based modeling is not used directly in VR systems. It is possible, however, to design an object using curves and then compute a polygonal representation of those curved patches. Various complexity polygonal models could be made from a single high resolution 'metaobject'.

I.7.3.6. Dynamic Geometry (aka morphing)

It is sometimes desirable to have an object that can change shape. The shape might simply be deformed, such a bouncing ball or the squash/stretch used in classical animation ('toons'), or it might actually undergo metamorphosis into a completely different geometry. The latter effect is commonly known as 'morphing' and has been extensively used in films, commercials and television shows. Morphing can be done in the image domain (2D morph) or in the geometry domain (3D morph). The latter is applicable to VR systems. The simplest method of doing a 3D morph is to precompute the various geometry's and step through them as needed. A system with significant processing power can handle real time object morphing.

I.7.3.7. Swept Objects & Surface of Revolution

A common method for creating objects is known as Sweeping and Surfaces of Revolution. These methods use an outline or template curve and a backbone. The template is swept along the backbone creating the object surface (or rotated about a single axis to create a surface of revolution). This method may be used to create either curve surfaces or polygonal objects. For VR applications, the sweeping would most likely be performed during the object modeling (creation) phase, and the resulting polygonal object stored for real time use.

I.7.3.8. Texture Maps & Billboard Objects

As mentioned in the section on rendering, texture maps (images) can be used to provide the appearance of more geometric complexity without the geometric calculations. Using flat polygonal objects that maintain an orientation towards the eye/camera (billboards) and multiple texture maps can extend this trick even further. Texture maps, even without billboard objects, are an excellent way to increase apparent scene complexity. Variations on the image mapping concept are also used to simulate reflections, etc.

I.7.4. Lights

Lighting is a very important part of a virtual world (if it is visually rendered). Lights can be ambient (everywhere), or located. Located lights have position and may have orientation, color, intensity and a cone of illumination. The more complex the light source, the more computation is required to simulate its effect on objects.

I.7.5. Cameras

Cameras or viewpoints may be described in the World Database. Generally, each user has only one viewpoint at a time (ok, two closely spaced viewpoints for stereoscopic systems). However, it may be useful to define alternative cameras that can be used as needed. An example might be an overhead camera that shows a schematic map of the virtual world and the user's location within it (You Are Here.)

I.7.6. Scripts and Object Behavior

A virtual world consisting only of static objects is only of mild interest. Many researchers and enthusiasts of VR have remarked that interaction is the key to a successful and interesting virtual world. This requires some means of defining the actions that objects take on their own and when the user (or other objects) interact with them. This i refer to generically as the World Scripting. I divide the scripts into three basic types: Motion Scripts, Trigger Scripts and Connection Scripts

Scripts may be textual or they might be actually compiled into the program structure. The use of visual programming languages for world design was pioneered by VPL Research with their Body Electric system. This Macintosh based language used 2d blocks on the screen to represent inputs, objects and functions. The programmer would connect the boxes to indicate data flow.

There is no common scripting language used in today's VR products. The commercial authoring packages, such as VR Studio, VREAM and Superscape all contain some form of scripting language. Autodesk's CDK has the "Cyberspace Description Format" (CDF) and the Distributed Shared Cyberspace Virtual Representation (DSCVR) database. These are only partially implemented in the current release. They are derived from the Linda distributed programming language/database system. ("Coordiantation Languages and their Significance", David Gelernter and Nicholas Carriero, Communications of the ACM, Feb 1992 V35N2). On the homebrew/freeware side, some people are experimenting with several Object Oriented interpretive languages such as BOB ("Your own tiny Object-Oriented Language", David Betz, DrDobbs Journal Sept 1991). Object Orientation, although perhaps not in the conventional class-inheritance mechanism, is very nicely suited to world scripting. Interpretive langauges are faster for development, and often more accessible to 'non-programmers'.

I.7.6.1. Motion Scripts

Motion scripts modify the position, orientation or other attributes of an object, light or camera based on the current system tick. A 'tick' is one advancement of the simulation clock. Generally, this is equivalent to a single frame of visual animation. (VR generally uses Discrete Simulation methods)

For simplicity and speed, only one motion script should be active for an object at any one instant. Motion scripting is a potentially powerful feature, depending on how complex we allow these scripts to become. Care must be exercised since the interpretation of these scripts will require time, which impacts the frame and delay rates.

Additionally, a script might be used to attach or detach an object from a hierarchy. For example, a script might attach the user to a CAR object when he wishes to drive around the virtual world. Alternatively, the user might 'pick up' or attach an object to himself.

I.7.6.2. Physical or Procedural Modeling and Simulation

A complex simulation could be used that models the interactions of the real physical world. This is sometimes referred to as Procedural Modeling. It can be a very complex and time consuming application. The mathematics required to solve the physical interaction equations can also be fairly complex. However, this method can provide a very realistic interaction mechanism. (for more on Physical Simulation, see the book by Ronen Barzel listed in the Computer Graphics Books section)

I.7.6.3. Simple Animation

A simpler method of animation is to use simple formulas for the motion of objects. A very simple example would be "Rotate about Z axis once every 4 seconds". This might also be represented as "Rotate about Z 10 radians each frame".

A slightly more advanced method of animation is to provide a 'path' for the object with controls on its speed at various points. These controls are sometimes referred to as "slow in-out". They provide a much more realistic motion than simple linear motion.

If the motion is fixed, some systems can precompute the motion and provide a 'channel' of data that is evaluated at each time instance. This may be a simple lookup table with exact values for each frame, or it may require some sort of simple interpolation.

I.7.6.4. Trigger Scripts

Trigger Scripts are invoked when some trigger event occurs, such as collision, proximity or selection. The VR system needs to evaluate the trigger parameters at each TICK. For proximity detectors, this may be a simple distance check from the object to the 3D eye or effector object (aka virtual human) Collision detection is a more involved process. It is desirable but may not be practical without off loading the rendering and some UI tasks from the main processor.

I.7.6.5. Connection Scripts

Connection scripts control the connection of input and output devices to various objects. For example a connection script may be used to connect a glove device to a virtual hand object. The glove movements and position information is used to control the position and actions of the hand object in the virtual world. Some systems build this function directly into the program. Other systems are designed such that the VR program is almost entirely a connection script.

I.7.7. Interaction Feedback

The user must be given some indication of interaction feedback when the virtual cursor selects or touches an object. Crude systems have only the visual feedback of seeing the cursor (virtual hand) penetrate an object. The user can then grasp or otherwise select the object. The selected object is then highlighted in some manner. Alternatively, an audio signal could be generated to indicate a collision. Some systems use simple touch feedback, such as a vibration in the joystick, to indicate collision, etc.

I.7.8. Graphical User Interface/Control Panels

A VR system often needs to have some sort of control panels available to the user. The world database may contain information on these panels and how they are integrated into the application. Alternatively, they may be a part of the program code.

There are several ways to create these panels. There could be 2D menus that surround a WoW display, or are overlaid onto the image. An alternative is to place control devices inside the virtual world. The simulation system must then note user interaction with these devices as providing control over the world.

One primary area of user control is control of the viewpoint (moving around within the virtual world). Some systems use the joystick or similar device to move. Others use gestures from a glove, such as pointing, to indicate a motion command.

The user interface to the VW might be restricted to direct interaction in the 3D world. However, this is extremely limiting and requires lots of 3D calculations. Thus it is desirable to have some form of 2D Graphical user interface to assist in controlling the virtual world. These 'control panels' of the would appear to occlude portions of the 3D world, or perhaps the 3D world would appear as a window or viewport set in a 2D screen interface. The 2D interactions could also be represented as a flat panel floating in 3D space, with a 3D effector controlling them.

I.7.8.1. Two Dimensional Controls

There are four primary types of 2D controls and displays. (controls cause changes in the virtual world, displays show some measurement on the VW.) Buttons, Sliders, Gauges and Text. Buttons may be menu items with either icons or text identifiers. Sliders are used for more analog control over various attributes. A variation of a slider is the dial, but these are harder to implement as 2D controls. Gauges are graphical depiction's of the value of some attribute(s) of the world. Text may be used for both control and display. The user might enter text commands to some command parser. The system may use text displays to show the various attributes of the virtual world.

An additional type of 2D display might be a map or locator display. This would provide a point of reference for navigating the virtual world.

The VR system needs a definition for how the 2D cursor effects these areas. It may be desirable to have a notion of a 'current control' that is the focus of the activity (button pressed, etc.) for the 2D effector. Perhaps the arrow keys on the keyboard could be used to change the current control, instead of using the mouse (which might be part of the 3D effector at present).

I.7.8.2. Three Dimensional Controls

Some systems place the controls inside the virtual world. These are often implemented as a floating control panel object. This panel contains the usual 2D buttons, gauges, menu items, etc. perhaps with a 3D representation and interaction style.

There have also been some published articles on 3D control Widgets. These are interaction methods for directly controlling the 3D objects. One method implemented at Brown University attaches control handles to the objects. These handles can be grasped, moved, twisted, etc. to cause various effects on an object. For example, twisting one handle might rotate the object, while a 'rack' widget would provide a number of handles that can be used to deform the object by twisting its geometry.

I.7.9. Hardware Control & Connections

The world database may contain information on the hardware controls and how they are integrated into the application. Alternatively, they may be a part of the program code. Some VR systems put this information into a configuration file. I consider this extra file simply another part of the world database.

The hardware mapping section would define the input/output ports, data speeds, and other parameters for each device. It would also provide for the logical connection of that device to some part of the virtual world. For example a position tracker might be associated with the viewer's head or hand.

I.7.10. Room/Stage/Area Descriptions

If the system supports the division of the virtual world into different areas, the world database would need multiple scene descriptions. Each area description would give the names of objects in scene, stage description (i.e. size, backgrounds, lighting, etc.). There would also be some method of moving between the worlds, such as entering a doorway, etc., that would most likely be expressed in object scripts.

I.8. World Authoring versus Playback

A virtual world can be created, modified and experienced. Some VR systems may not distinguish between the creation and experiencing aspects. However, there is currently a much larger body of experience to draw upon for designing the world from the outside. This method may use techniques borrowed from architectural and other forms of Computer Aided Design (CAD) systems. Also the current technologies for immersive VR systems are fairly limiting in resolution, latency, etc. They are not nearly as well developed as those for more conventional computer graphics and interfaces.

For many VR systems, it makes a great deal of sense to have a Authoring mode and a Playback mode. The authoring mode may be a standard text editor and compiler system, or it may include 3D graphic and other tools. Such a split mode system makes it easier to create a stand alone application that can be delivered as a product.

An immersive authoring ability may be desirable for some applications and some users. For example, an architect might have the ability to move walls, etc. when immersed, while the clients with him, who are not as familiar with the system, are limited to player status. That way they can't accidentally rearrange the house by leaning on a wall.

II. VR Information Resources

The following information is provided to direct the interested reader to more information on virtual reality. It is not a complete listing of all sources. Many of the VR reference books listed below contain resource listings that have more complete descriptions of some of the products and services offered.

Toni Emerson of the HITL has put together a more extensive list of resources. Her list can be found on the ftp site ftp.u.washington.edu in the directory public/Virtual-Reality/HITL/reports. Look for irvr.txt and any emerson.... documents. At this writing the most current is emerson.B.93.2.txt. I have borrowed liberally from Toni's list. I hope she will forgive me. Toni's report is far more likely to be updated in the future than this document.

Bill Cockayne maintains an very good listing of on-line services, newsgroups, etc. as vr_sites.txt on ftp.apple.com.

There are several commercial services that provide much more extensive listings of VR resources.

The one that I have found to be the most extensive is Sophistech's VR Sourcebook. This is available both in printed and electronic form.

II.1. NewsGroups and Mailing Lists

There are two different styles of group communication on. First there are the News Groups, which were originally part of Usenet. These are distributed to news repositories on the various host systems and are browsed and replyed to via a news reader. Details of news access vary between systems. Contact your local system administrators for information on methods available to you. Second, there are the mail lists services automatically by 'list servers' (aka listserv). These distribute their contents via email directly to the mailbox of the individual subscribers.

Subscribing to a mail list requires sending an email message to either an individual or an automated list-server service. Generally, the list-servers note your email address from the mail header and read the body of the message for special commands. The one you want is "subscibe <listname> <your full name>". Replacing <listname> with the name of the newslist you want and <your full name> with your *real* name, not your login name.

II.1.1. Some recommended Usenet groups:

comp.graphics
comp.graphics.visualization
comp.graphics.digest
comp.research.japan
comp.robotics
comp.simulation
alt.cyberpunk and alt.cyberpunk.tech often concerns topics related to VR, though that is not the focus of the discussions themselves.
alt.cyberspace has pretty light-hearted discussions on the present and future implementation of cyberspace in the world.

II.1.2. VR News Groups with Mail List Echos

The following two news groups are directly aimed at the VR community and are also available as mail list echos.

Sci.virutal-worlds (aka: virtu-l) Moderated by Toni Emerson, Aaron Pulkka and Michael Almquist (Human Interface Technology Lab Moderating Group). Send a mail message to
listserv@uiucvmd.bitnet
with a body of
subscribe virtu-l <full_name>
Moderator: gbnewby@alexia.lis.uiuc.edu.(Greg Newby)

Sci.virtual-worlds.apps (aka: vrapp-l) co-moderated by Bob Jacobson and Mark DeLoura. Send a mail message to:
listserv@uiucvmd.bitnet
with a body of
subscribe vrapp-l <full_name>

II.1.3. Mailing Lists

Glove-list: Subscribe by sending an email message to
listserv@boxer.nas.nasa.gov
with a body of
subscribe glove-list <your full name, not login id>
Post to: glove-list@winn30.nas.nasa.gov
Moderator: jet@boxer.nas.nasa.gov

Head-Trackers mailing list: Subscribe by sending e-mail to
trackers-request@qucis.queensu.ca
with an informal request (not handled by automated system)
post to: trackers@qucis.queensu.ca

REND386 : two mail lists, one for announcements and one for general discussions. Subscribe by sending an email message to
Majordomo@sunee.uwaterloo.ca
with a body of either or both of the following lines:

subscribe rend386-announce
subscribe rend386-discuss
Moderated by the creators of REND386 - Dave Stampe and Bernie Roehl

Iris On-Line: based on the SGI monthly news magazine. To subscribe, email:
list-manager@sgi.comm
with a body of
subscribe nyn-emag

VIGIS-L: discussion of uses of VR interfacces for Geographic Information Systems (GIS) and spatial information support systems. Moderator: Thomas Edwards. To subscribe email:
listserv@uwavm.bitnet
with a body of
Subscribe VIGIS-L (yourname)

Amiga VR list: Administerd by Ethan Dicks <erd@kumiss.cmhnet.org> To subscribe send a message to
listserv@kumiss.cmhnet.org
with a body of
"subscribe amigavr-list <your first name> <your last name>".

DIS-List: information on the Distributed Interactive Simulation protocol and NPS software impementation. Send an mail message requesting to be added to the list to:
dis-maint@taurus.cs.nps.navy.mil

II.2. Internet FTP Sites

II.2.1. Sites in the North America

ftp.u.washingon.edu public/virtual-worlds (home of sci.virtual-worlds) and public/Virtual-Reality

(HITLab archives)

stein.u.washingon.edu - alternative to ftp.u.washingon.edu

sunee.uwaterloo.ca (129.97.50.50) (home of REND386 (freeware VR library/package)

ftp.apple.com (130.43.2.3) (sites list, Macintosh VR, CAD projects info)

taurus.cs.nps.navy.mil: (Info on DIS and NPSNET, including C library)

avalon.chinalake.navy.mil (129.131.31.11) (lots of geometry files)

wuarchive.wustl.edu (128.252.135.4) mirror stein VR, usenet archive

sunsite.unc.edu (152.2.22.81) /pub/academic/computer-science/virtual-reality (virtual reality demos, iris info, glasses, mirrors some of stein.u.washington.edu, uforce info)

world.std.com bcs/vr (Boston Computer Society's VR area)

ftp.ncsa.uiuc.edu (USA, supercomputer center really high end VR) in the ./VR area

src.doc.ic.ac.uk (146.169.2.1) (usenet archive /usenet...)

mom.spie.org International Society for Optical Engineering

conf4.darpa.mil (192.160.51.7) info on ALSP a high level battle simulation protocol in alsp/doc

II.2.2. Overseas FTP Sites

ftp.ipa.fhg.de (Germany)

wench.eco.jcu.edu.au /pub/sega - LC glasses info

tauon.ph.uimelb.edu.au pub/papers/galilean (real time rendering hardware)

ftp.iunet.it ftp/vender/Atma Real Light radiosity renderer demo & info

eta.lut.ac.uk (158.125.96.29) UK-VR-SIG ftp archive. check out public/pc/swoopvr.zip

II.3. On-line Services & BBS

There are many computer bulletin boards and on-line services that support VR discussion and development. I am personally involved on several. My email address is given at the beginning of this paper.

I am the sysop of the CompuServe CyberForum (Go CyberF). This is one of the most active online discussions and the libraries contain a large number of VR programs, demos, concept papers, and an (incomplete) echo of the sci.virtual-worlds news group. For information on CompuServe, call (800)848-8990 or (614) 457-8650

The WELL (Whole Earth 'Lectronic Link) has a VR discussion area (GO VR). For information on joining The WELL, call(415) 332-4335 or modem (415)332-6106. You can also telnet into the well as 'well.sf.ca.us' and sign on as newuser.

The Byte Information Exchange (BIX) has a conference on VR: join virtual.world. To join BIX, call 1-800-695-4882 (2400 Baud, No Parity, 8 data, 1 stop bit). BIX is also available via telnet as 'x25.bix.com', and enter "BIX" at the first user name prompt.

America On-line reportedly also has a VR section. "VIRTUS" - virtual reality conference hosted by Virtus Corp. To find contact AOL, call 1-800-827-6364. They might ask for an extension #, try 5894

GENIE has a VR discussion and partial echos of sci.virtual-worlds on the Space and Science Roundtable and also the Radio and Electronics Round Table. Contact J Randall Severy - (GEnie: RSEVERY, CompuServe: 76166,3477, Internet: ge!severy@uunet.uu.net) (Info on joining GENIE???)

The Diaspar VR Network is a BBS dedicated to VR. Diaspar includes a number of 'VNET' or virtual BBS subsystems that are run by other individuals. Sense8 has one VNET on Diaspar that is used for their customer support. There are also some interactive multiperson 3D programs available on Diaspar, most notably the chess game "Mate" from VRontier Worlds. Diaspar can be reached at (714) 831-1776 (voice), 9600 Baud: 714-376-1234, 1200 Baud: 714-376-1200. Diaspar is available from Internet sites via Telnet as diaspar.com (192.215.11.1) It is also available from the PC Pursuit long distance network - 800.736.1130. On first login use the name "Diaspar" (be sure to use capital D and lowercase iaspar.) This gets you to the BBS login area and you can get set up with your username and password.

The AMULET BBS (Santa Monica, CA). Data access: (310)453-7705.

SENSE/NET (801) 364-6227 (Salt Lake City, Utah) (I have not been able to successfully connect with this BBS)

Zarno BBS at (706) 860-2927 (Atlanta GA), carries RIME, an international mail system that is used on many BBS's and which has recently started a VR conference. (also threads in C and CAD rime networks)

Colton, CA BBS with the RIME echo...The number is (909) 783-7802

Toronto Virtual Reality SIG BBS(416) 631-6625, 16.8K baud. I

Virtual Space Driver [MD] (301) 424-9133

VRontier Worlds BBS [WI] 608-873-8523 (6pm-7am CST weekdays, 24hrs on weekends) Includes the electronic home of PCVR magazine. Note that this is a business voice line during the day.

Houston Game Designer BBS [TX]713-251-0734

Hacker-Art (Italy) 39-55-485997

II.4. Local VR Interest Groups

This section provides a listing of local and (some) national VR interest groups. Many of these have regular meetings with invited speakers and presentations. They are one of the best ways to get to know other people involved in VR in your area.

II.4.1. Groups in USA

Los Angeles VRSIG: contact Virtual Ventures/Dave Blackburn, 1300 The Strand, Suite A, Manhattan Beach, CA 90266 Voice:(310) 545-0369 email: breeder@well.sf.ca.us (I am a member of this group, which meets at the Electronic Cafe International on 18th Street, Santa Monica, CA)

Chicago VRSIG: c/o Nina Adams, 3952 Western Ave, Western Springs, Chicago, IL 60558, Voice: (708)246-0766 email: 71052.1373@compuserve.com

San Francisco VR Group, Contact Linda Jacobson, Verge (Virtual Reality Group), 16050 Kings Creek Rd., Boulder Creek, CA 95006; Voice: 415-826-4716. email:lindaj@well.sf.ca.us

Houston TX: CyberSociety, 3336 Richmond Ave. #226, Houston, TX 77098-3022, Voice: 713/520-5020, FAX: 713/520-7395, NETt: specdyn@well.sf.ca.us

Stoughton WI: Andrew's VEE-AR Club, c/o Andrew or Tom Hayward, 624 Jackson Street, Stoughton, WI 53589

Boston Computer Society VR Group, c/o Paul Matthews - Director, Building 1400, One Kendal Square, Cambridge, MA 02139, Voice: 508 921 6846 24hr, Voice: 617 252 0600, email:pgm@world.std.com

Louisville, Kentucky: VRSIG, c/o Andrew Prell, PO Box 43003, Louisville, KY 40253, Voice:502 495-7186, email: andrewp@well.sf.ca.us

Norman Oklahoma:VR Awarness Consotium: 405-447-3276, email: gsullivan@aardvark.ucs.uokno.edu or gas@well.sf.ca.us

Redondo Beach Virtual Reality Group, Contact Mike Heim 2104 Bataan Road #2 Redondo Beach CA 310.542.1199

The Virtual Worlds Society, 4739 University Way, Suite 1628, Seattle, WA 98105. Contact: Joel Orr , email: JOEL_ORR@mcimail.com./tel: 1-800-vws-7711

Distributed Simulations Applications Research Consortium, 1320 18th Street, San Francisco, CA 94107. Tel: 415-861-1317/Fax: 415-431-9368. Tom Hargadon - Managing Director, Carl Eugene Loeffler - President.

VR Alliance for Students and Professionals (VRASP), PO Box 4139, Highland Park, New Jersey 08904-4139. Email: kaugust@caip.rutgers.edu or 71033.702@compuserve.com.

II.4.2. Groups in Other Coutntries

Belgium: Genootschap voor Virtuele Realiteit (Society for Virtual Reality), Philippe Van Nedervelde, Lichtaartsesteenweg 55, B-2275 Poederlee - Lille, Belgium

Canada: Univ. of Waterloo VR Group, c/o Rick Kazman (or c/o Bernie Roehl), Dept of Computer Science, Univ. of Waterloo, Waterloo, Ontario, N2L 3G1, Voice: (519) 888-4870 (R.Kazman), (519) 885-1211 x2607 (B.Roehl), email: broehl@sunee.uwaterloo.ca

Toronto Canada: Toronto VRSIG, c/o Caius Tenche, (416) 242-3119, email: caius.tenche@canrem.com

Vancouver BC: Canadian Virtual Worlds Society . Contact Derek Dowden 604.739.8080 or Andrew Moreno <amoreno@unixg.ubc.ca>

England: UK-VRSIG, R.Hollands@Sheffield.ac.uk Robin Hollands A&CSE Dept.Sheffield University Mappin Street Sheffield S1 3JD -- UK -- voice +44 (0)742 730066 fax +44 (0)742 731729 or S.M.Clark@lut.ac.uk

France: Les Virtualistes, 90 Avenue de Paris, 92320 Chatillon, France, Voice: 1/47 35 65 48, FAX: 1/47 35 85 88

Germany: Fraunhofer Institute for Computer Graphics & German Working Group on Virtual Reality (Related to Technical University in Darmstadt, and to the Computer Graphics Centre (ZGDV) in Darmstadt), Mr. Wolfgang Felger, Wilhelminenstr. 7, W-6100 Darmstadt, F.R.G., Voice ++49-6151-155122, Fax.: ++49-6151-155199, email: felger@igd.fhg.de, email list: vr@igd.fhg.de

South Africa VRSIG c/o Roger Layton, Chairman, PO Box 72267, PARKVIEW, 2122, South Africa, TEL: +27-11-788-5938, FAX: +27-11-442-5529, email: 74660.2154@compuserve.com

II.5. Journals & Newsletters

CyberEdge Journal. Excellent professional newsletter, Ben Delaney, Editor, #1 Gate Six Road, Suite G, Sausalito, CA 94965, Voice: 415 331-EDGE (3343), FAX: 415 331-3643, email: 76217.3074@compuserve.com, email:bdel@well.sf.ca.us., ISSN# 1061-3099. CyberEdge Journal also produces a series of special industry reports on specific sub areas and application domains of VR.

PCVR Magazine. For the home-brew enthusiast. includes Code Disks, Editor: Joseph Gradecki, PO Box 475, Stoughton, WI 53589, VOICE/FAX: (608) 877-0909, email: 70711.257@compuserve.com or PCVR@fullfeed.com.

Presence: Teleoperators & Virtual Environments. Professional Tech Papers and Journal., MIT Press Journals, 55 Hayward St, Cambridge MA 02142, (800) 356-0343, (617) 628-8569, (617) 253-2889 (9-5 EST), Fax: (617) 258-6779, email: hiscox@mitvma.mit.edu, ISSN 1054-7460

Real Time Graphics, 2483 Old Middlefield Way #140, Mt. View, CA 94043-2330, Tel: 415-903-4924, Fax: 415-967-5252, e-mail: roy_w_latham@cup.portal.com newsletter, 10/yr., mid-to-high end technology, in-depth product coverage, tutorials

VR Monitor: Frank Dunn, Editor, Matrix Information Services, 18560 Bungalow Drive, Lathrup

Village, MI 48076, Voice: (313) 559-1526, email: matrix@well.sf.ca.us, email: 70117.2546@compuserve.com

PixElation, VRASP c/o Karin August P. O. Box 4139 Highland Park, NJ 08904-4139 USA, kaugust@caip.rutgers.edu

Virtural Reality News, Brian Lareau, Editor, Magellan Marketing Inc. 32969 Hamilton Courts Suite 215, Farmington Hills Mich. 48334 313-488-0330, email: larryv@msen,com

VR-NEWS (The Virtual Reality Newsletter), Cydata Publishing Limited, P.O. Box 2515, London N4 4JW, England, Tel. & Fax: +44 (0)81-292-1498, Managing Editor: Mike Beavan (email: 100024.1425@compuserve.com)

Virtual Reality Report, Meckler Publishing, Sandra Helsel, Editor in Chief, Meckler Corporation, 11 Ferry Lane, Westport CT 06880, Voice: (203)226-6967 (Meckler also produces a number of conferences and various other VR and computer publications)

VR Systems, SIG-Advanced Applications, Inc.,1562 First Avenue, Suite 286, New York, NY 10028, Tel: 212-717-1318, Fax: 212-861-0588/89.

INTERTECH (German language), published in Vienna, Austria by IDG and ICON, fax: +43 1 802 21 76 or e-mail: 100276,1277

IRIS Universe: The Magazine of Visual Computing. Published quarterly by Silicon Graphics, Inc., 2011 North Shoreline Boulevard, Mail Stop 415, Mountain View, CA 94039-7311. Subscriptions are available to qualified users. ISSN 1061-6608

Pixel Vision. Subscription information: Pixel Vision, Box 1138, Madison Square Station, New York, NY 10159. This magazine was new in 1992. It is published in French and English.

Realta' Virtuale. Via Rombon 11, 20134 Milano, Italy. 6 issues/year. Voice +39 02-26412898 Fax: +39 02-26413279. Diego Montefusco, editor. Email: montefus@ghost.dsi.unimi.it.

II.6. Professional Societies

There are several major professional computer associations that publish respected journals related to Virtual Reality.

II.6.1. ACM

The Association for Computing Machinery (ACM) has a number of special interest groups whose journals and newsletters often have VR related articles. SIGGRAPH is the SIG for Computer Graphics. Their national convention is The Event for Computer Graphics each year. The '93 conference will be in Anahiem CA, August 1-6. SIGCHI is the SIG for Computers and Human Interaction. This group has published a lot of research on new methods of interacting with computers, including a number of new VR applications. Contact info:

Association for Computing Machinery, 1515 Broadway, 17th Floor, New York, NY 10036, (212) 869-7440, email: info.Membership@siggraph.org (for membership info), email:

info.Siggraph93@siggraph.org (for conference info)

II.6.2. IEEE

The Institute of Electrical and Electronics Engineers (IEEE) has a computer graphics SIG that publishes an execellent journal called "IEEE Computer Graphics and Applications". Subscriptions are $26/year for society members, $47 for ACM or other society members, (six issues). (The Jan 1994 issue will have a concentration on Virtual Reality!) The IEEE also publishes a large number of books and conference proceedings. Contact info:

IEEE Computer Society, PO Box 3014, Los Alamitos, CA 90720-9804, (714) 821-8380, (800) 272-6657 (Publication orders), email: membership@compmail.com

IEEE Engineering in Medicine and Biology Magazine : the quarterly magazine of the Engineering in Medicine & Biology Society. ISSN 0739-5175.

II.6.3. Other professional Societies and Journals

Computer Graphics Forum: Journal of the European Association for Computer Graphics. Amsterdam : North Holland. ISSN 0167-7055.

Human Factors. Journal of the Human Factors Society. ISSN 0018-7208.

Optical Engineering. Published monthly by the Society of Photo-optical nstrumentation Engineers (Bellingham, WA: SPIE). ISSN 0091-3286.

Simulation. Published monthly by Simulation Councils, Inc. Editorial and Circulation: Society for Computer Simulation (SCS) P.O. Box 17900, San Diego, California 92177. Tel:619-277-3888. ISSN 0037-5497.

II.7. Books

This section provides a bibliography of some books on VR, Computer Graphics and some related subjects. It also provids a listing of science fiction books that deal in part with VR and Cyberspace.

II.7.1. VR Reference Books

Most of these are aimed at the less technical reader, but some will include lots of good technical details. Many will include executable programs on disk, some with source code. Some of the intro books contain bibliographies and listings of companies with VR products, including pictures.

"Adventures in Virtual Reality", Tom Hayward, Que Books, 1993, ISBN 1-56529-208-1 (includes PC disk with VREAM world and other demos)

"Artificial Reality II", Myron Krueger, Addison-Wesley, 1991, ISBN: 0-201-52260-8

"Computers as Theatre", Brenda Laurel, Addison-Wesley, 1991

"CYBERARTS: Exploring Art & Technology" Edited by Linda Jacobson, Miller Freeman, Inc ISBN

0-87930-253-4

"Cyberspace - First Steps", MIT Press, 1992 (collection of essays on VR), ISBN 0-262-52177-6

"Flights of Fantasy, Programming 3-D Video Games in C++", Chris Lampton, Waite Group, 1993, ISBN 1-878739-18-2 (intro to flight simulators, includes excellent intro to fast polygon rendering techniques, etc, incl PC Disk w/source code)

"Garage Virtual Reality", Linda Jacobson, SAMS, (to be published Oct 1993) ISBN 0-672-30389-2 (A how-to book for the home brew enthusiast) (incl PC Disk)

"Silicon Mirage: The Art and Science of Virtual Reality", Steve Aukstakalnis & David Blatner, Peach Pit Press 1992,ISBN 0-938151-82-7

"The Metaphysics of Virtual Reality " , Heim, Michael, Oxford University Press, 1993. ISBN 0-19-508178-1

"Virtual Reality", Howard Rheingold, Summit Books, 1991, ISBN 0-671-69363-8 (one of the first books on VR published. a bit dated now.)

"Virtual Reality and the Exploration of Cyberspace", Francis Hamit, Sams Publishing, ISBN 0-672-30361-2. (incl PC disk and a very extensive bibliography)

"Virtual Reality : Applications and Explorations" ed. Alan Wexelblat, Academic Publishers, c1993. ISBN 0-12-745045-9

"Virtual Reality Creations", Dave Stampe Bernie Roehl & John Eagan, Waite Group Press, 1993 ISBN 1-878739-39-5 (*the* book on Rend386)

"Virtual Reality - En bog om den kunstige virkelighe" (Danish Language) Christian Schade and Morten Steiniche. Borgens Forlag A/S, Denmark, march 1993. ISBN 87-418-6751-3

"Virtual Reality Playhouse", Nicholas Lavroff, Waite Group Press, 1992 ISBN 1-878739-19-0 (includes PC disk, apps are at most WoW interactive animations)

"Virtual Reality Systems", ed R.A.Earnshaw, M.A.Gigante, H.Jones.ISBN: 0 12 227748 Published April 1993.

"Virtual Reality: Theory, Practice, and Promise", Sandra Heisle & Judith Roth, Meckler Corp, 1990 LC Call number BD331 .V57 1991

"Virtual Reality: Through the New Looking Glass", Ken Pimentel & Kevin Teixeira, Intel/Windcrest/McGraw-Hill, 1993 ISBN 0-8306-4064-9

"Virtual Worlds and Multimedia" ed. N. Magnenat Thanlmann & D. Thanlmann Wiley, c1993.

"Virtual Worlds : A Journey in Hype and Hyperreality ", Woolley, Benjamin. Blackwell, 1992. LC CALL NUMBER: BD331 .W866 1992

II.7.2. VR Directories and Conference Proceedings

"Virtual Reality Sourcebook", Panos, Gregory (ed.). (1992). SophisTech Research, 6936 Seaborn St., Lakewood, CA 90713-2832. Telephone: 310-421-7295. (probably the most complete and extensive commercial directory available)

VR Bibliographic Index. Updated quarterly since 1989. Matrix Information Services, 18560 Bungalow Drive, Lathrup Village, MI Email: matrix@well.sf.ca.us.

Virtual Reality Handbook. Available for $248 from Pasha Publications, Inc. 1616 N. Ft. Myer Dr., Suite 1000. Tel: 703-528-1244/Fax: 703-528-1253.

Virtual World Builder: Virtual Reality and Synthetic Digital Environment Products Catalogue and Resource Guide. Spectrum Dynamics, 2 Greenway Plaza, Suite 640, Houston, TX 77046-0203. Tel:713-520-50020/Fax:713-871-1196. Internet: specdyn@well.sf.ca.us/Compuserve: 70761,1647.

"Virtual worlds : real challenges : papers from SRI's 1991 Conference on Virtual Reality" Meckler, c1992. LC CALL NUMBER: QA76.9.H85 C445 1991

Emerging markets for virtual reality. Boston, MA (214 Harvard Ave., Boston 02134) : IGI Consulting, LC CALL NUMBER: HD9696.C62 E583 1992

Conference on Virtual Reality, Artificial Reality, and Cyberspace (2nd : 1991 : San Francisco, Calif.) Beyond the vision : the technology, research, and business of virtual reality : proceedings of Virtual Reality '91, the Second Annual Conference on Virtual Reality, Artificial Reality, and Cyberspace, San Francisco, September 23-25, 1991 ; Westport, CT : Meckler, c1992. 237 p. : ill. ; 28 cm. LC CALL NUMBER: QA76.9.H85 C67 1991

"Virtual reality : an International Directory of Research Projects" Meckler, 1993.

"Virtual reality : a selected bibliography", McLellan, Hilary. Educational Technology Publications, 1992. LC CALL NUMBER: Z5643.I57 M4 1992

II.7.3. Government Papers

Durlach, N. I., Aviles, W. A., Pew, R. W., et. al. (eds.). (1992, March). Virtual Environment Technology for Training (VETT). (BBN Report No. 7661.). Cambridge, MA: Bolt Beranek and Newman, Inc.

Molendi, Gloria and Patriarca, Matteo. (1992). Virtual Reality: Medical Researches. Technical Report Number 1/92. Milano, Italy: Universita' degli Studi di Milano. Available via anonymous ftp from ghost.dsi.unimi.it, in the directory : pub2/papers/patriarca/medVR.txt.

United States Congress. (1992). Virtual Reality : Hearing Before the Subcommittee on Science, Technology, and Space of the Committee on Commerce, Science, and Transportation, and United States Senate. New Developments in Computer Technology. Washington, DC: U.S. GPO. (United States. Congress. Senate Hearing; 102-553). LC CALL NUMBER: KF26 .C697 1991e

Defense Science and Technology Strategy, Director of Defence Research and Engieneering July 1992 FOFT 02.nov. 003558

National Academy of Sciences, National Research Council, Committee on Virtual Reality Research & Development, Computer Generation Technology Group. (1993). Report on the State-of-the-Art in Computer Technology for the Generation of Virtual Environment. Report is yet unpublished.

II.7.4. Computer Graphics Books

"Computer Graphics (Principles and Applications)", Foley, Van Dam, Feiner & Hughes, 2nd Edition, Addison Wesley, 1990 ISBN 0-201-12110-7 (This is The Bible of Computer Graphics. The classic text book.)

"Visualization Graphics in C", Lee Adams, Windcrest/McGraw-Hill, 1991, ISBN 0-8306-3487-8

"Fundamentals of Three Dimensional Computer Graphics", Alan Watt, Addison Wesley, 1989, ISBN 0-201-15442-0

"New Trends in Animation and Visualization", Thalmann & Thalmann, John Wiley & Sons, 1991, ISBN 0-471-93020-2

"Physically-Based Modeling for Computer Graphics", Ronen Barzel, Academic Press, 1992, ISBN 0-12-079880-8

"3-D Computer Animation", John Vince, Addison-Wesley ISBN #0-201-62756-6.

"3D Computer Graphics: A User's Guide for Artists and Designers", Andrew Glassner.

"Making Them Move; Mechanics, Control and Animation of Articulated Figures", (Book and Video Package) Edited by Norman I. Badler (U Pennsylvania), Brian A. Barsky (U CalBerkeley) and David Zeltzer (Media Lab, MIT),Morgan Kaufmann Publishers, ISBN Book/Video Package: 1-55860-155-4 Book only: 1-55860-106-6 Tape only: 1-55860-154-6

"Virtual humans and simulated agents", Badler, Norman I. Oxford University Press, 1993.

"Simulating Humans: Computer Graphic, Animation and Control.", Badler, Norman I. May 1993, Oxford University Press

Virtual Worlds and Multimedia, Edited by Nadia Magnenat Thalmann and Daniel Thalmann, pub John Wiley & Sons, 1993, $59.95

"True Three-Dimensional Graphics", Michael Hyman, Brady Press, 1985

"Programmin in 3 Dimensions: 3-D Graphics, Ray tracing and Animation": Christopher Watkins & Larry Sharp, M&T Books 1992

II.7.5. Related Books

The following books, while not directly about VR technology, can provide some background ideas and concepts for VR.

"Pictorial Communication in Virtual and Real Environments", Stephen R Ellis (ed), Taylor & Francis, 1991, ISBN: 0-74840-008-7

Visual data interpretation : 10-11 February 1992, San Jose, California / Bellingham, Wash. : SPIE, c1992. vii, 159 p. : ill. ; LC CALL NUMBER: QA76.575 .V57 1992

"Eccentric Spaces", by Robert Harbison. Boston: David R. Godine, 1988. $10.95, Subtitled, "A voyage through real and imagined worlds."

"The Design and Analysis of Spatial Data Structures", Haman Samet, Addison Wesley. 1990, ISBN: 0-201-50255-0

"Applications of Spatial data Structures", Hanan Samet, 1990, ISBN: 0-201-50300-X

"The Visual Display of Quantitative Information", Edward Tufte, Graphic Press, 1983

"Envisioning Information", Edward Tufte, Graphic Press 1990

"Virtual Worlds, A Journey in Hype and Hyperreality", by Benjamin Woolley, published by Blackwell, Oxford, 1992.

"Eye and Brain. The psychology of seeing (4th edn)", Gregory, R. L., Weidenfeld and Nicholson, 1990, ISBN: 297-82042-7 (pbk)

"Mirror Worlds" by David Gelernter Oxford Univ. Press 1992 ISBN 0-19-507906-2

"The craft of text editing", Craig Finseth (Interface Design)

"The Society of text", Edward Barrett. (Interface Design)

II.7.6. Fiction Books Related to VR

The following list of Cyberpunk and other VR related books was collected from posts to Sci.virtual-worlds and CompuServe's CyberForum. I cannot vouch that they are all truely VR related.

Piers Anthony's "Killobyte."
Stephen Barnes- Street-Lethal, Gorgan's Child
Greg Bear - Blood Music
David Brin - Earth
John Brunner - Shockwave Rider, The Sheep Look Up, Jagged Orbit
William S. Burroughs Naked Lunch, Nova Express, The Ticket that Expoloded
Pat Cadigan - Mindplayers, Synners, etc.
Orson Scott Card's Ender's Game
Samuel Delany Nova
Philip K. Dick - Do Androids Dream of Electric Sheep, Flow My Tears, the Policeman Said The Game-Players of Titan Ubik VALIS The Divine Invasion The Transmigration of Timothy Archer

William Gibson - Neuromancer, Count Zero, Mona Lisa Overdrive, Burning Chrome, Virtual Light
Stanislav Lem.
Mark Leyner - My Cousin, My Gastroenterologist
Larua Mixon - Glass Houses
Tom Maddox: Halo
Larry Niven's Known Space series of books - really enjoyable stuff.
Marge Piercy, "He, She and It"
Thomas Pynchon: Gravity's Rainbow, V, The Crying of Lot 49, Vineland
Kim Stanley Robinson The Gold Coast
Frank Robinson - The Dark Beyond the Stars
Rudy Rucker - Wetware, Software
Lucius Shepard - Life During Wartime
John Shirley -The Eclipse triology, Freezone
Bruce Sterling - Islands in the Net, The Artificial Kid, Globalhead, Mirrorshades: The Cyberpunk Anthology
Neal Stephenson - Snow Crash
Amy Thompson - Virtual Girl
James Tiptree, Jr. - The Girl who was Plugged In
Vernor Vinge - True Names and Other Dangers, A Fire Upon the Deep
Walter John Williams - Hard-Wired, Voice of the Whirlwind
David Wingrove - Chung-Kuo (series)
Zelaney & Saberhaven - Coils

"Simulations - 15 tales of virtual reality", edited by Karie Jacobson, Citadel Twilight Press. ISBN 0-8065-1406-X
includes: The Crying of Lot 49
1. "The Veldt" (1950) by Ray Bradbury
2. "Overdrawn at the Memory Bank" (1976) by John Varley
3. "Walking the Moons" (1990) by Jonathan Letham
4. "Virtual Reality" (1993) by Michael Kandel
5. "Dogfight" (1985) by Michael Swanwick and Willian Gibson
6. "The Shining Dream Road Out" (1993) by M. Shayne Bell
7. "The Total Perspective Vortex" (1980) by Douglas Adams
8. "Plug-in Yosemite" (1985) by Marc Laidlaw
9. "This Life and Later Ones" (1987) by George Zebrowski
10. "Steelcollar Worker" (1992) by Vonda McIntyre
11. "I Hope I shall Arrive Soon" (1980) by Philip K. Dick
12. "From Here to Eternitape" (1992) by Daniel Pearlman
13. "Pretty Boy Crossover" (1986) by Pat Cadigan
14. "A Guide to Virtual Death" (1992) by J.G. Ballard
15. "The Happy Man" (1963) by Gerald Page
16. Bibliography of VR in fiction

II.8. VR Research Labs & Academia

This list is woefully incomplete. There is a much more extensive one available on ftp.u.washington.edu in the virtual-worlds FAQ area. It was neglected for a long time and became very dated. Toni Emerson and others at HITL are endeavoring to correct this deficiency.

CAD Institute, 4100 E. Broadway, Suite 180, Phoenix, AZ 85040, (800) 658-5744, Dean: John Morrison 76307.1552@compuserve.com

HITL (Human Interface Technology Laboratory), University of Washington, FJ-15, Seattle, WA 98195, (206) 543-5075, Director: Dr. Thomas A. Furness III (publishes HITLab Review, contact Alden Jones at above address or alden@hitl.washington.edu)

Visual Systems Laboratory, Institute for Simulation and Training Laboratory, University of Central Florida, 12424 Research Parkway, Suite 300, Orlando, FL 32826, Director: Dr. Michael Moshell

UNC Laboratory, Univerisity of North Carolina, Chapel Hill, Computer Science Department, Chapel Hill, NC 27599-3175, Director: Fredrick Brooks

US Navy - Cyberview, David Sarnoff Research Center, Mark Long, CN5300, Princeton NJ 08543-5300

Naval Postgraduate School, Graphics and Video Lab, Department of Computer Science, Naval Postgraduate School, Monterey, CA 93943-5100, Contacts: Dave Pratt, pratt@cs.nps.navy.mil, Prof. Mike Zyda, zyda@trouble.cs.navy.mil

Computer Graphics Laboratory, University of Alberta, Edmonton, Canada, Mark Green, Associate Professor (mark@cs.ualberta.ca) (403) 492-4584

National Center for Supercomputing Applications (NCSA) at the University of Illinois at Urbana-Champaign. Contact: Gregory B. Newby, Assistant Professor, Graduate School of Library and Information Science. Room 417 DKH, 1407 W. Gregory Drive, Urbana, IL, 61801. gbnewby@alexia.lis.uiuc.edu

Networked Virtual Art Museum, Studio for Creative Inquiery, Carnigie Mellon University, Pittsburgh PA 15213, Carl Loeffler, (412) 268 3452, cel+@andrew.cmu.edu

II.9. Companies Involved with Virtual Reality

Companies involved with or producing VR products. The following is a composite of several lists i have found on Internet and CompuServe. It is by no way an exhaustive list. There are commercial companies that sell such lists (and more info). Some of these are included in the list below.

1-900-VIRTUAL (yes a 1-900 number for VR) cost $1.25/minute

3D Imagetek , 4525-B San Fernando Rd., Glendale, CA 91204, Phone: (818) 507-1269 Fax: (818) 507-8537, Helmet Mounted Displays (HMDs)

3DTV Corporation, P.O. Box Q, San Francisco, CA 94913-4316, Voice (415) 479-3516, Fax 415 479 3316 (LCD shutter glasses, other homebrew products)

Advanced Gravis Computer Technology Ltd. 7400 MacPherson Ave. #111, Burnaby, B.C. V5J 5B6 Canada. 604-434-7274. MouseStick (optical joystick for AT bus card) , 3D Sound Card.

Ascension Technology Corporation. P.O. Box 527, Burlington, VT 05402. P.O.Box 527, Burlington, VE 05402, (802) 655-7879. "Bird" family of magnetic position sensors.

Autodesk, Inc. 2320 Marinship Way, Sausalito, CA 94965. (800) 525-2763 Cyberspace Developers Kit

Avatar Partners,13090 Central Avenue, Suite 3, Boulder Creek, CA 95006 USA Tel: (408) 338-6464 Fax: (408) 338-6462 Email: avatarp@well.sf.ca.us (Amber C++ programming package and VR Trader application)

CAE Electronics Ltd. C.P. 1800 Saint-Laurent, Quebec, H4L 4X4 Canada. 514-341-6780. Head-mount displays.

CiS. 285 Littleton Rd., Ste. 3, Westford, MA 01886. 603-894-5999, 508 692-2600 (fax). Geometry Ball Jr. (6D joystick).

Clarity, Nelson Lane, Garrison, NY 10524, Phone: (914) 424-4071 Fax: (914) 424-3467,Auditory display products

Covox, Inc. 675 Conger Street, Eugene, Oregon 97402, Phone: (503) 342-1271 Fax: (503) 342-1283, "Voicemaster Key System" - PC voice interface $150 and other sound related products

Crystal River Engineering. 12350 Wards Ferry Rd., Groveland, CA 95321. 209-962-6382. Convolvotron (4 channel 3D audio card for PC).

Dimension International, Zephyr One Calleva Park, Aldermaston, Berkshire RG7 4QZ , Phone: 07 34 810 077 Fax: 816 940, "Superscape" PC-based VR, uses 34020 graphics card to speed things up.

Dimension Technologies, Inc., 176 Anderson Avenue, Rochester, NY 14607, vox: 716-442-7450, fax: 716-442-7589, DTI 100M, projection video stereoviewing system.

Division Ltd. Quarry Rd., Chipping Sodbury, Bristol B517 6AX England. 44-0454-324527. 80860-based VR. "Vision VR" hi-end system with multiple 80860s. PC-based, lo-end system with one 80860 and one Sharp HSSP per eye.

Division Inc, (US branch of Division Ltd) Dave Bonini, Voice: (415) 364 6067 Fax: (415) 364 4663 Email: daveb@division.com

Domark Software, 1900 South Norfolk St #202 San Mateo CA 94402 voice 415.513.8929, VR Studio package

Exos 8. Blanchard Road, Burlington, MA 01803. 617229-2075. (617) 229-2075, Hand-worn interface devices.

Fake Space Labs. 935 Hamilton Ave., Menlo Park, CA 94025. 415-688-1940. BOOM (stereo viewer on articulated arm).

Focal Point Audio 1402 Pine Ave. Suite 127, Niagara Falls, NY 14301. 415-963-9188. 3D audio boards for Mac and PC.

Future Vision Technologies, Inc., 701 Devonshire Drive, Champaign, IL 61820, (217) 355-3030, Fax: (217) 355-3031, Sapphire Multimedia card

Global Devices, 6630 Arabian Circle, Granite Bay CA 95661, (915)791-2558, fax:915-791-4358. 6D controller & navigator - joystick/ball devices.

Gyration, Inc. 12930 Saratoga Ave., Bldg. C, Saratoga, CA 95070. 408-255-3016. GyroPoint (optically sensed gyroscopic sensors).

Haitex Resources, Inc., Charleston, South Carolina, 803-881-7518, Haitex X-Specs 3D for the Amiga line. (glasses should work with PC circuit)

Horizon Entertainment, P.O. Box 14020, St. Louis MO 63178-4020, (800) ILLUSION (455-8746), Virtuality Entertainment Games

Iwerks, Burbank CA, 818-841-7766, Reactor and other LBE systems

Leep Systems, 241 Crescent St., Waltham, MA 02154,, Phone: (617) 647-1395 Fax: (617) 899-9602"Cyberface" HMDs, optics for HMDs.

Lego Education Systems 800-527-8339, Lego Dacta computerized Lego sets

Lepton Graphics Systems, 2118 Central SE, Suite 45.Albuquerque, NM 87106, voice: (505) 843-6719 email: scott@lepton.yenta.abq.nm.us "Lepton Virtual Reality Toolkit", C and assembler library for creating interactive 3d graphic applications.

Lightscape Graphics Software, 2 Berkeley St, Suite 600, Toronto ON M5A 2W3 Canada 416.862.2528 fax 416.862.5508 email rrecker@attmail.com

Logitech Inc. 6505 Kaiser Drive, Fremont, CA 94555. 415-795-8500. (Cyberman, 6D mouse and head tracker).

Magic 3-D, PO Box 1377, Alexander City, Alabama, 35010, 205-329-3767, 3D and garage VR stuff. (Ray Bolt), VR HowTo booklet

Media Magic, Phone: (415) 662-2426, P.O. Box 507 Nicasio, CA 94946, Superb catalog of books and videos on VR, Chaos, Fractals, etc.

MegageM, 1093 Adria, Santa Maria CA 93454, 805-349-1104, email: Daniel Wolf 70250.626@compuserve.com. garage VR and stereoscopic products for Amiga

Mira Imaging, Inc. , 2257 South 1100 East, Suite 1A, Salt Lake City, Utah 84106, (800) 950-6472, Phone: (801) 466-4641 Fax: (801) 466-4699"Hyperspace" - 3D digitizing and modeling software

Myron Krueger, Artificial Reality, 55 Edith, Vernon, CA 06066, Phone: (203) 871-1375,Custom-designed virtual world environments

Pasha Publication, P.O. Box 9188, Arlington, VA 22219, Voice 800-424-2908, VIRTUAL REALITY HANDBOOK: Products, Services and Resources

The University of Pensylvania,Center for Technology Transfer, 3700 Market St., Suite 300, Philadelphia, PA 19104, Phone: (215) 898-9585 Fax: (215) 898-9519, "Jack" - full body sensor positioning system

Polhelmus, Inc. 1 Hercules Drive, P.O. Box560, Colchester, VT 05446. 802-655-3159. Polhemus (3Space 6D magnetic tracker).

Pop-Optix Labs. 241 Crescent Street, Waltham, MA 02154. 617-647-1395. Specialized optics for headmount displays.

The Quest Company 3117 W. Holland Ave. Fresno, CA (209) 222-5301NorthCad Pro 3d V 9.8 - CAD package that can output files for REND386.

Reel-3D Enterprises, Inc, PO BOX 2368, Culver City CA 90231, (310) 837-2368, Toshiba LCD Shutter glasses

Real World Graphics, Phone: 0992 554 442 Fax: 554 827, 5 Bluecoats Ave., Hertford SG14 1PB. 80860-based VR systems. "SuperReality" with multiple 80860s and texturing ASICs on VME cards. Lo-end "Reality PC" has a four-processor PC card with stereo framebuffer. Specialising in flight simulation.

Reflection Technology, 230 Second Ave., Waltham, MA 02154, Phone: (617) 890-5905 Fax: (617) 890-5918, "Private Eye" LED-based monochrome HMD.

RPI Advanced Technology Group, POB 14607 San Francisco, CA 94114, Phone: (415) 777-3226, "The Personal Simulator" and "HMSI" (Head Mounted Sensory Interface device) VGA2x dual channel VGA card, and other products.

Sense8 Corporation. 1001 Bridgeway, P.O. Box 477, Sausalito CA 94965. 415-331-6318, 415-331-9148 (fax). VR software and systems (for PC, Sun & Silicon Graphics) .

SimGraphics Engineering Corp. 1137 Huntington Drive, South Pasadena, CA 91030. 213-255-0900. Systems configuration house/OEM VR equipment supplier.

Simsalabim Systems, Inc. PO Box 4446; Berkeley CA 94704-0446; (800) 3D TODAY
Internet: scope@well.sf.ca.us, Fax: 1 800 922 FAXX, Cyberscope stereoscopic viewer.

Shooting Star Technology ,1921 Holdom Ave., Burnaby, BC, V5B 3W4, Phone: (604) 298-8574
Fax: (604) 298-8580,Mechanical position sensor (approx $1499)

SophisTech Research, 6936 Seaborn Street, Lakewood, CA 90713-2832, (310) 421-7295, (800) 4VR SOURCE (orders only), Virtual Reality Sourcebook

Spaceball Technologies, Inc. 2063 Landings, Sunnyvale, CA 94043. 408-745- 0330. Spaceball (6D joystick).

Spectrum Dynamics, 3336 Richmond Ave. #226, Houston, TX 77098-3022, Voice: 713/520-5020, Fax : 713/520-7395, email: specdyn@well.sf.ca.us, VR equipment distributers, VAR, etc

StereoGraphics. 21 71-H East Francisco Blvd., San Rafael, CA 94901. 415- 459-4500. Stereoscopic displays & LCD Shutter Systems.

StereoCAD, 655 S. Fair Oaks Ave, Suite A-117, Sunnyvale CA 94086 408.245.5201, fax 408.245.5202. RT Texture VR program.

Straylight. 150 Mount Bethel Road, Warren, NJ 07050. 908-580-0086. VR authoring systems, CyberTron game system.

Subjective Technologies. 1106 Second Street, Suite 103, Encinitas, CA 92024. 619-942-0928. Tools for controlling virtual environments.

TiNi Alloy Co. 1144 65th Street, Unit A, Oakland, CA 94608. 510-658-3172. Tactile feedback systems.

Transfinite Systems Co, Inc PO Box N, MIT Branch Post Office, Cambridge MA 02139-0903, voc 617-969-9570, Gold Brick device - connects Nintendo controllers to Macintosh.

Transition State, 497 S El Molino Ave, Suite 304, Pasadena CA 91101 818/568.8640
Virtual Research 1313 Socorro Ave., Sunnyvale, CA 94089. 408-739-7114. Flight Helmet (head mounted display).

Virtual Presence, 25 Corsham St, London, N1 6DR England, 071 253 9699 fax 071 490 8968, denise@presence.demon.co.uk TCAS Dataware. Lycra bodysuit with sensors.

Virtual Technologies. P.O. Box 5984, Stanford, CA 94309. 415-599-2331. Instrumented gloves and clothing.

Virtual Worlds, 5201 Great America Parkway Suite 320, Santa Clara CA 95054 - design studio.

Virtuality Group, 3 Oswin Rd., Brailsford Industrial Park, Leicester LE3 1HR, Phone: 0533 542 127 Fax: 548 222, "Virtuality" arcade system

Vision Research Graphics, 99 Madbury Road, Durham, NH 03824, vox: 603-868-2270, fax: 603-868-1352, Resellers of Haitex LCD glasses w/PC driver & software

The Vivid Group. 317 Adelaide Street, W., Suite 302, Toronto, Ontario, M5V IP9 Canada. 416-340-9290. 416-348-98()9 (fax). Mandala (VR authoring systems).

ViviStar Consulting, 7015 E Aster Dr; Scottsdale Az 85254; (602) 483 3123, AppleLink: ViviStar CompuServe: 73067,542 Internet: ViviStar@ACM.org 3D graphics library for Macintosh

VREAM. 2568 N. Clark Street, #250, Chicago, IL. 60614. 312-477-0425 VR authoring systems.

VRontier Worlds of Stoughton, Inc. 809 E. South Street, Stoughton, WI. 53589 (608) 873-8523 FAX: (608) 877-0575 Sales: 800 VR TIER1, Tier1 HMD, MATE game, etc

World Design Inc. 5348 1/2 Ballard Ave. Seattle, WA 98107, Phone: (206) 782-8630, Robert

Jacobson - VR consultants, Information Designers

Xtensory Inc. 140 Sunridge Drive, Scolls Valley, CA 95066. 408-439-0600. Tactile feedback systems.