6. Virtual Environments

Francis Balaguer and Angelo Mangili
Computer Graphics Laboratory
Swiss Federal Institute of Technology
Lausanne, Switzerland

The last decade has been marked by the development of the computer as a tool in almost every domain of human activity. One of the reasons for such a development was the introduction of human-friendly interfaces which have made computers easy to use and learn. The most successful interface paradigm so far has been the Xerox Parc Desktop metaphor popularized among computer users by the Macintosh. However, if the desktop metaphor is well suited to interacting with two-dimensional worlds, it starts to show limitations when interacting with three dimensional worlds. Recently, various specialized research programs on advanced concepts for human–machine interaction have focused on this problem and have gradually made possible the development of new input devices and displays for interacting with remote or computer generated worlds. Rather than keyboard input, interaction is based on voice, gesture and hand manipulation; displays are rethought to closely match human vision capabilities yielding in the development of head mounted or head coupled display concepts. The goal is to simulate operator presence in remote or computer synthesized worlds. In this chapter, we present this new interface metaphor, the perceptual and technological requirements to simulate it, 3D input devices and displays, and 3D interaction techniques.

6.1. Virtual Reality

6.1.1. Historical Background

Virtual reality (VR) is not a new concept even if the oxymoron "artificial reality" was recently introduced by Krueger (1983). Sutherland (1965) introduced the key concepts of immersion in a simulated world, and of complete sensory input and output, which are the basis of current VR research. At MIT, at the beginning of the 1980s, a limited three-dimensional virtual workspace in which the user interactively manipulates 3D graphical objects spatially corresponding to hand position, was developed (Schmandt 1983). In 1984, NASA started the VIVED project (Virtual Visual Environment Display) and later the VIEW project (Virtual Interactive Environment Workstation). As described in Fisher et al. (1986), the objective of the research at NASA Ames is to develop a multipurpose, multimodal operator interface to facilitate natural interaction with complex operational tasks and to augment operator awareness of large-scale autonomous integrated systems. The application areas on which NASA Ames focuses, are telepresence control, supervision and management of large-scaled information systems and human factors research. Even though NASA's research interested researchers, VR was not introduced to the general public until June 6, 1989 at two trade shows by VPL and Autodesk. Both companies presented devices and head-mounted displays for interacting with virtual worlds. Since then, VR has captured the public imagination and lots of work has been done to explore the possibilities of VR in new areas of application such as medicine, chemistry, scientific visualization.

6.1.2 Application

VR is more than just interacting with 3D worlds. By offering presence simulation to users as an interface metaphor, it allows operators to perform tasks on remote real worlds, computer generated worlds or any combination of both. The simulated world does not necessarily have to obey natural laws of behavior. Such a statement makes nearly every area of human activity, a candidate for a VR application. However, we can identify some application areas as more straightforward than others.

6.1.2.1. Telepresence, Telerobotics

Hostile environments such as damaged nuclear power plants make it difficult or impossible for human beings to perform maintenance tasks. However, for the foreseeable future, robots will not be intelligent enough to operate with complete independence, but will require operator intervention to perform tasks in changing or unanticipated circumstances (Zeltzer 1990). Telepresence aims to simulate the presence of an operator in a remote environment to supervise the functioning of the remote platform and perform tasks controlling remote robots. In supervisory control modes, a VR interface provides the operator with multiple viewpoints of the remote task environment in a multi-modal display format that can be easily reconfigured according to changing task priorities. The operator can investigate the remote site either free-flying or through telerobot mounted cameras. To perform remote operations that cannot be performed autonomously by robots, the operator can switch to interactive control. In this telepresence mode, he is given sufficient quantity and quality of sensory feedback to approximate actual presence at the remote site. The operator's stereoscopic display is linked to the robot 3D camera system and his arm is made spatially correspondent with the robot arm. NASA Ames developed a telepresence prototype application where the operator interacts with a simulated telerobotic task environment (Fisher et al. 1986).

6.1.2.2. Large Data Set Exploration

Many three-dimensional applications in scientific visualization consist of the study of multi-dimensional physical phenomena. In such systems, the computer model generates data representing the behavior of the model under special initial conditions. Study of complex phenomenon such as a thunderstorm requires a tremendous volume of data which raises the problem of data interpretation. In scientific visualization, the VR interface can help scientists explore the multi-dimensional graphical representation of their data at various levels of detail using interactive camera control and stereoscopic displays. The scientist is free to fly within his simulation data and therefore to focus interest on any part of its simulation, to study it in detail or to allocate supercomputer time for a more precise simulation (Brooks 1988).

6.1.2.3. Architecture Walkthrough

One application area of VR can be architecture. Brooks (1986) and Airey et al. (1990) presented a system to explore virtual buildings, designed but not yet constructed. The object of the system was visualization of the building to permit the architect to prototype a building and to iterate with his client on the detailed desiderata for it. Using a video projector for a wider field of view, stereo techniques and a special 3D device, he enabled the user to interactively walk-through the virtual building as if it was built. Even if in that case, the purpose of the application was presentation of an already designed building, an extension of such an application can be thought of as a tool to help the designer visualize and explore the spaces he is creating as part of the design process.

6.1.2.4. Other Areas

Examples in previous sections are not exhaustive. At the University of North Carolina, they explore the use of head-mounted displays in areas such as molecule analysis and medical imaging (Chung et al. 1989). Nasa Ames build a system to interactively explore the surface of Mars based on Viking images (Jackoby 1990) and apply VR to information management (Fisher et al. 1986). At the Human Interface Technology Laboratory (HITL) of the University of Washington, they are working on VR for air traffic controllers where the controller would be able to see with a head-mounted display every plane in the sky around the airport and would be able to start a radio connection with the plane by touching its 3D graphical representation (Stewart 1991).

6.1.3. Perceptual Requirements for a Virtual Reality System

We humans are experienced in interacting with three-dimensional worlds. Our sense of vision enables us to orient ourselves in space, and provides others cues for locomotion and communication. Our mind is highly trained to interpret images and communication is often more effective through images, graphs, diagrams than through words. Traditional computer configuration allows us to interact visually with virtual worlds through a window (the screen) on that world. We can change what we see on the window, but the window itself remains static in our own world. The virtual world resides inside the computer, we are exterior to it.

The major characteristic of VR is inclusion: being surrounded by an environment. VR places the participant within information. This simulation of presence inside a computer generated world introduces a general paradigm shift in the way we perceive the interaction task with the machine. Bricken (1990) gives the HITL's opinion on changes of perspective introduced by simulation of presence:

"The extension of field of view coupled with stereoscopic display produces the feeling that we cease from viewing a picture on the screen to start experiencing the sensation of being in a place. We shift from external users exercising rights to internal participant exercising responsibilities, from observing to experiencing, from interfacing with a display to inhabiting an environment. This sensation of being surrounded make us forget about the virtuality of the world we are exploring."

Every human–machine interaction task is a bi-directional communication between a user and the machine. The user specifies input and the computer responds to it by updating its output.

What are the input and output channels required to realize simulation of presence? In a traditional computer configuration, inputs and outputs are well defined. Input is specified through the keyboard and the mouse while output consists of updating a display. VR, which assumes the fact that human beings are well equipped to interact with 3D worlds, wants to make users interact with virtual worlds in the same way they interact with real worlds, thus making the interaction task much more natural and reducing training. Observing the way we interact with the real world, it is possible to identify the new input and output channels required to simulate immersion.

- **output** channels are those by which humans receive information from the world. They correspond to our senses: vision, touch and force perception, hearing, smell, taste. Analyzing crudely how we use our senses, we can say that vision is our privileged mean of perception, while hearing is mainly used for verbal communication, to get information from invisible parts of the world or when vision does not provide enough information. Touch and force perception is essential for interacting with another object during manipulation tasks while smell and taste are mostly secondary. Therefore, critical output channels are graphical display, audio output, touch and force information output. Visual feedback must match as closely as possible human vision capabilities, i.e. binocular vision, and wide field of view. Audio feedback must be able to synthesize sound, to position sound sources in 3D space and can be linked to a speech generator for verbal communication with the computer. Touch feedback must transmit force data necessary for precise manipulation.

- **input** channels are those with which humans emit information and interact with the environment. We interact with the world mainly through locomotion and manipulation. We communicate information by means of voice, gestures and facial expressions. Gestural communication as well as locomotion make full body motion analysis desirable. However, hand motion tracking is sufficient for almost every applications as the hand offers many more degrees-of-freedom (DOF) concentrated in a small area than any other part of the body. Moreover, the fact that the hand is our privileged manipulation tool make hand motion tracking a critical input for interacting with virtual worlds. Viewpoint specification requires real time motion tracking of the user's head, and eventually eye, in order to update displayed stereo images in coordination with user movements. Verbal communication with the computer or other users makes voice input necessary.

Figure 6.1 presents output and input channels of a typical VR computer configuration.

6.2. Interaction Devices for Virtual Reality

Currently, a set of devices, hand measurement hardware, head-mounted displays, as well as 3D audio systems, speech synthesis or recognition systems are available on the market. At the same time, many research labs are working on defining and developing new devices such as force-feedback devices, tactile gloves, eye-tracking devices, or on improving existing devices such as head-mounted displays and tracking systems. In the next sections, we are going to present various existing devices and a perspective of development for the future.

Figure 6.1. Virtual reality computer configuration (Furness 1987).

6.2.1. Tracking Devices

Commercial and experimental 3D position tracking devices have used acoustic, magnetic, mechanical, and optical methods for reporting 3D position and orientation.

Acoustic systems use the time-of-flight principle to estimate the position of an object in space. Because the speed of sound varies if ambient air density changes, these systems have poor accuracy over a large range. Furthermore, it is difficult to use them to measure orientation.

Mechanical linkage systems have been built in the past (Sutherland 1968). Not only have they a limited working range, but the friction inertia of the system and the mechanical linkage attached to the user greatly restrict its motion.

Magnetic tracking devices have been the most successful and the Polhemus 3Space Isotrack, although not perfect, is the most common one. A source generates a low frequency magnetic field detected by a sensor (see Figure 6.2). The main problems with the Polhemus, is that its performance is affected by any conducting materials present in the environment. Moreover, the Polhemus has a limited working range (~ 1 m^3) and a update rate (~ 16 Hz) which is barely enough for interactive applications.

Although most optical tracking systems seem to have failed as commercial products for VR, the method is appealing mainly because it is relatively insensitive to environmental distortions and has a large working environment. The optical tracking system presented by Wang et al. (1990) is composed of three cameras on the helmet and an environment consisting of a room where the ceiling is lined with a regular pattern of infrared LEDs flashing under the system's control. The 2D positions of the LED images inside field of view are reported in real-time and the 2D image position and the known 3D positions of the LED are used to compute the position and orientation of the helmet in space. Multiple users can be present in the same environment without interfering. The main problems are the weight of the camera assembly, and the fact that the system needs a room where LEDs are installed.

Figure 6.2. Polhemus source and sensor

6.2.2. Head-Mounted Displays

Most head-mounted display systems developed in the last decade (Chung et al. 1989), present the rich 3D cues of head-motion parallax and stereopsis. Head-mounted displays, designed to take advantage of human binocular vision capabilities, present the general following characteristics:

- headgear with two small display devices (generally LCD color screens), each optically channeled to one eye, for binocular vision.
- special optics in front of the screens, for wide field of view
- a tracking system for precise location of the user's head in real time.

Figure 6.3 presents the internal components of an head-mounted display developed at NASA Ames. Displays are small LCD TV screens and the computer output has to be predistorted to compensate for the radial distortion introduced by the wide angle optics.

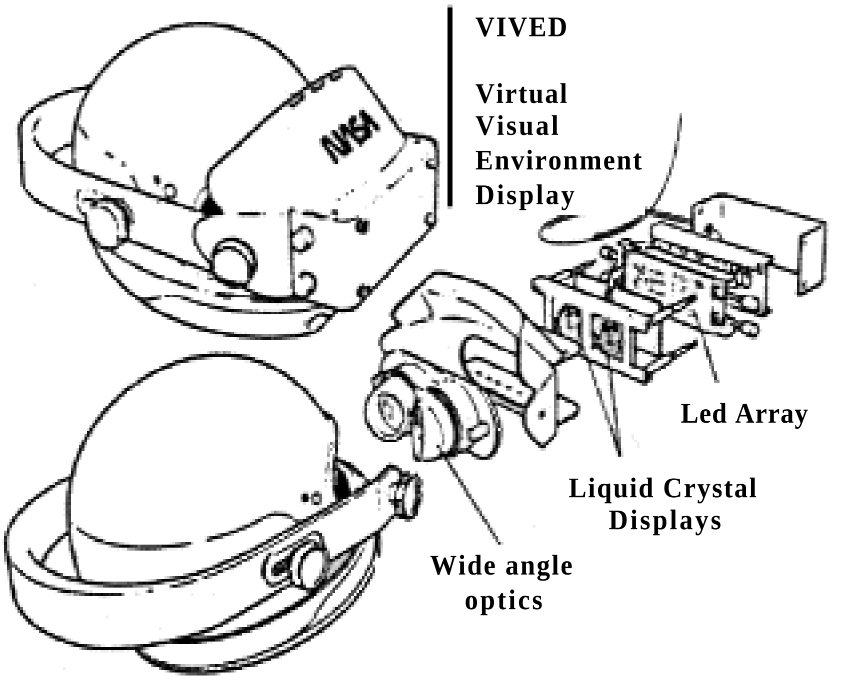

Figure 6.3. Virtual environment display system (Reproduced from Fisher et al. (1986)).

Figure 6.4. A see-through head-mounted display

Figure 6.5. VPL EyePhone

6.2.3. Hand Measurement Devices

Hand measurement devices must sense both the flexion angles of the fingers and the position and orientation of the wrist in real-time. Image based techniques have been used to measure both channels directly from observation of user movement. However, since interpretation of the moving images is required, this technique tends to be slow and imprecise, even when LEDs are used to identify key points on the user to simplify image processing task (Ginsberg and Maxwell 1986). The Z-glove (Zimmerman et al. 1987) from VPL Research, performed position tracking with electronics transducers mounted on side of the palm. This method of tracking fails if there is not a direct line-of-sight between the transducers and the set of three receivers.

Currently, the most common hand measurement device is the DataGlove (see Figure 6.6) from VPL Research. The DataGlove consists of a lightweight nylon glove with optical sensors mounted along the fingers. In its basic configuration, the sensors measure the bending angles of the joints of the thumb and the lower and middle knuckles of the others fingers, and the DataGlove can be extended to measure abduction angles between the fingers. Each sensor is a short length of fiberoptic cable, with a light-emitting diode (LED) at one end and a phototransistor at the other end. When the cable is flexed, some of the LED's light is lost, so less light is received by the phototransistor. Attached to the back is a 3Space Isotrack system (see previous section for description) to measure orientation and position of the gloved hand. This information, along with the ten (fifteen to measure abduction angles, in the extended configuration) flex angles for the knuckles is transmitted through a serial communication line to the host computer. Knuckle data can be sampled at up to 60 Hz.

Figure 6.6. VPL DataGlove

6.2.4. Other Devices

The DataGlove and head-mounted displays are not the only devices to have been developed in the last few years.

Some people have tried to extend the concept of the mouse to 3D. Called a wand or bat in the literature, 3D mice (Ware and Jessome 1988) are generally built around a Polhemus tracker. Some buttons are sometimes added to the device. The problem of such devices is that they are absolute position devices. You must move the hand grabbing the device, according to the movement desired for the object. This is often tiring and requires a bit of concentration, especially when the display upgrade rate falls under 10 Hz.

In order to address this problem, Spatial Systems designed an incremental device called the Spaceball (see Figure 6.7). It is composed of a rigid sphere containing strain gauges mounted on a plastic base in order to offer a comfortable rest position for the operator hand and arm. The position and orientation are specified by rotating or pushing the sphere in a certain direction. Although the sphere moves only slightly, the force and torque applied are measured and an incremental position and orientation is transmitted, at a configurable rate, to the host computer. The Spaceball is well suited to moving objects or virtual cameras in three-dimensional space. The metaphor based on the fact that the ball you grab is the object you want to move is easy to integrate, thus requiring reduced training.

Figure 6.7. The Spaceball

6.2.5. Perspectives

Even if the hardware presented above is a tremendous step towards the VR computer configuration presented in part one (see Figure 6.1), many major problems remain unresolved to achieve full effectiveness:

- *developing high-resolution color displays*. The technology used in current head-mounted displays is mainly based on LCD screens for reasons of weight and energy consumption. The resolution is too low (less than video resolution) for high quality images. Even if we can expect higher resolution LCD screens and video standard in the future, some people have taken a totally different approach. HITL has engaged a research project on using laser beams to display the pictures directly on the retina, hence solving the problem of resolution and wide field of view.

- *developing headgear* of a reasonable size and weight, that allows a wide-screen view of the graphics display screen superimposed on the real world. This is a difficult optical problem. The wide angle optics used nowadays make superposition of computer images onto the real-world difficult because the real-world pictures have to be predistorted to compensate for the radial distortion introduced by the optics.

- *developing tracking systems* that have the range of a room with 1 mm resolution and response time of a few milliseconds or less. An ultimate tracking system would require real-time high precision tracking of multiple persons in a large environment. It should also be insensitive to interference from the environment. Even if some progress has been made with the optical tracker, the ultimate tracker is still far in the future.

Other research focuses on creating force-feedback devices (Minsky et al. 1990; Iwata 1990; Luciani 1990), eye trackers (Jacob 1990), tactile feedback gloves, and on improving graphics performance of workstations (Fuchs et al. 1989). Even if a real VR system is still far off, existing devices allow us to build real and useful applications and to study the software tools needed for interaction.

6.3. Interaction Techniques

Interacting with three-dimensional worlds is not fundamentally different from interacting with two dimensional worlds, in terms of interaction tasks. Basic interaction tasks are still the same. We still need to specify a viewpoint, to select objects and to position them in space, to specify values, states, or text (Foley et al. 1990). However, in order to simulate presence, the mouse has been replaced by hand measurement hardware which has become the main input channel for interacting with the virtual world. How shall we use this device combined with tracking information to specify viewpoint, values and states? How shall we use direct manipulation to position an object? How can we control objects with many degrees of freedom? Solving these complex problems is the aim of current research. Hence, the next sections will present a starting point for a solution based on the work of Zeltzer at MIT. We present the different levels of abstraction that can be used to model objects in a virtual environment, and how the DataGlove can be used for direct manipulation of each type of object.

6.3.1. Abstraction of a Privileged Device, the Glove

When using an input device, one can poll directly the input channels and hard code a meaning for each of them according to the program current state. If such an approach is possible with a simple device such as the mouse, it is much more difficult to poll a device such as the DataGlove because of its 10 or 15 DOF for the hand plus 6 DOF for position and orientation. The DataGlove must be abstracted into a virtual device at the software level, which sends out higher level events.

The DataGlove comes with a library that polls the hardware and composes event records containing flexion angles, location of the hand, a timestamp and a posture number. Postures are identified by correlating finger angles and posture numbers using a lookup table. At MIT, Studmann et al. (1989) evaluated the abstraction proposed by VPL as not sufficient for whole hand interaction because VPL offers only direct manipulation and state input through postures. Studmann identified three ways of approaching whole hand interaction:

- as a method for direct manipulation where the user guides object of the virtual world as if he would manipulate elements of the real world.
- as an abstracted graphical input device such as a button, valuator, or locator.
- as a gestural language.

Studmann analyzed hand motion in terms of its basic components: hand position and orientation, finger flexion angles, and organized the components into a taxonomy of hand motion summarized by the following table (Figure 6.8).

Figure 6.8. Hand motion taxonomy (Studmann et al. 1989)

The first row and first column of the table, correspond to conventional logical input devices. Whole hand input can be used in terms of the existing interaction metaphor. Finger postures offer a natural way to initiate events and set modes of interaction. Flex angles can be used as valuators and the hand itself is used as a 3D cursor. The lower 2x2 part of the table corresponds to more complex composite movements that are familiar from everyday social interactions. These do not really correspond to classical input metaphors. Recognition of gestures requires the use of artificial intelligence pattern matching because a gesture will never be reproduced exactly the same way twice. Gestures could be associated with some actions (like bye-bye with quit).

As use of classical interaction metaphors is well defined in the literature (Foley et al. 1990), the next section will present the use of direct manipulation with the various types of objects populating the virtual world.

6.3.2. Direct Manipulation (Guiding)

Guiding requires the user to provide the parameters required by some program. Guiding is interactive and direct and requires real-time system response. Typically in interacting with virtual environments, guiding is useful when positioning objects in space, or to specify a viewpoint. As guiding techniques require detailed specification of movement by the user, real-time feedback is necessary.

6.3.2.1. Viewpoint Specification

In previous sections, we pointed out the importance of the visual output channel to create the illusion of presence. On the other hand, viewpoint specification is a key technique which must be as natural and intuitive as possible so that the user is no longer conscious of it and can concentrate on the application task.

The head motion input channel provides all the information required for viewpoint specification. The kinesthetic correspondence between the user's head and the virtual camera viewpoint provide a highly naturalistic for of interaction. However, such a straightforward spatial correspondence is not always desirable or possible. Unconstrained motion with respect to real space is necessary for large displacement purposes. Several recent papers have proposed and studied the use of various kinematic or dynamic metaphors (Ware and Osborne 1990), Turner et al. 1991), such as "flying-vehicle", to control the virtual camera motion using a six DOF devices. Hence, we can think of the virtual camera as a two part mechanism, one part is a mechanical system which embodies the behavior of the metaphor, the other part is the camera itself with a 3 DOF mount for local rotations. Then the camera is controlled through two input channels, hand motion can be used to control the metaphor while head motion is used to control local rotation while moving. Hence, using a flying vehicle metaphor, the hand can be used to specify direction and speed of motion, while head motion is used to allow the user to look around while flying.

It is generally accepted that no one particular type of camera control metaphor is appropriate for all tasks. Scene exploration, object inspection and editing do not have the same requirements in terms of camera motion. In telepresence applications, on the other hand, user movements are constrained by the ability of the robot to move in the real world.

6.3.2.2. Object Manipulation

In graphical simulations, guiding is useful as a means to specify the details of object motion. However, since humans are not very good at attending to more than a few tasks at once, the power of guiding tools diminishes rapidly as the number of simultaneous DOF to be controlled increases. A solution to this problem is abstraction to hide irrelevant details so that the user can focus on general concepts appropriate to the task at end.

Zeltzer (1990) has identified four levels of abstraction (structural, procedural, functional, agents) from passive objects (structural), to autonomous objects (agents), and analyzed how direct manipulation should be used with each level of abstraction. At the structural level, the object is described as its kinematic structure and physical attributes. Procedural abstraction is a mechanism for defining processes that control rigid or non rigid object motion, such as collision detection, inverse kinematics, forward dynamics or elastic deformation, independently of the structure of the object. Functional abstraction consists of associating procedures with objects or object subassemblies. Functional units allow decomposition of many DOF system such as a human body, into a set of small, constrained, manageable subsystems with fewer DOF. For example, we can define a walk functional unit where we associate the lower part of the body with a walk engine (Boulic et al. 1990). Since the action to be performed is known, functional constraints can be applied so that the walking subsystem can be controlled with fewer parameters. The higher level of abstraction consists in defining agents. An agent is composed of a structural definition, a set of functional units that defines its behavior repertoire, and some means for selecting and sequencing behaviors according to variation in environment.

At a structural level, direct control of the object motion can be useful when few DOF are involved, especially if we consider that we are highly accustomed to position and orient objects using our hands. Thus, the DataGlove can be really useful to manipulate objects, at least through manipulation of the root node of the kinematic hierarchy. Guiding procedural abstraction consists of supplying a stream of value as input to procedures which are subsequently applied to models. Direct manipulation of the camera can be performed this way by "plugging" the output of a device such as the DataGlove or the Spaceball to the input of a controller which will apply the transformation on the camera object. Guiding functional units is similar to guiding procedural abstractions. Controlling agents through direct manipulation consists of changing the environment to vary its behavior by, for example, specifying a position to reach through the use of a 3D locator, or using the 3D locator as an obstacle for the agent to avoid.

6.4. Conclusion

In this chapter, we have presented the application fields of VR for the short term future. We have identified the perceptual requirements for a VR computer configuration in order to simulate presence, examined the currently available devices and their limitations in offering complete sensory input–output. We have studied the problem of interacting with three dimensional worlds, focusing on direct manipulation of objects and viewpoint through the use of the DataGlove.

Major problems remain. Improvement of current head-mounted displays and real-time trackers is necessary to reach full simulation of presence. On the software side, simulation of presence and new device capabilities require the definition of new interaction metaphors for direct manipulation of objects, and the development of techniques to associate them with behaviors. On-going research is addressing these problems and some progress can be expected in the foreseeable future. However, the current technology allows developers and application designers to increase the effectiveness of 3D application interfaces, hence increasing users creativity and comfort while reducing training requirements.

Acknowledgements

We would like to thank Russell Turner, Enrico Gobbetti and Ronan Boulic for their help reviewing this chapter.

Notes

DataGlove™, EyePhone™ are registered trademarks of VPL Research Inc, Redwood City, CA, USA.

3Space™, Isotrack™ are registered trademarks of Polhemus Navigation Sciences, Colchester, VT, USA.

Spaceball™ is a registered trademark of Spatial Systems Inc.

References

Airey J, Rohlf JH, Brooks Jr FP (1990) Towards Image Realism with Interactive Update Rates in Complex Virtual Building Environments, *Proceedings ACM Siggraph Symposium on Interactive 3D Graphics*, 1990, Vol.24, No2, pp.41-50.

Boulic R, Magnenat-Thalmann N, Thalmann D (1990) A Global Human Walking Model with Real-time Kinematic Personification, *The Visual Computer*, Vol 6(6), Dec. 1990, Springer, pp.344-358.

Bricken W (1990) Virtual Reality: Directions of Growth, Notes from the Siggraph 1990 Panel, *usenet paper, group sci.virtual-worlds,* Nov.

Brooks Jr FP (1986) Walkthrough - A Dynamic Graphics System for Simulating Virtual Buildings, *Proceedings 1986 ACM Workshop on Interactive Graphics*, Oct 23-24, pp.9-21.

Brooks Jr FP (1988) Grasping Reality Through Illusion - Interacting Graphics Serving Science, *Proceedings CHI 88*, May 15-19, pp.1-11.

Chung JC, Harris MR, Brooks Jr FP, Fuchs H, Kelley MT, Hughes J, Ouh-young M, Chung C, Halloway RL, Pique M (1989) Exploring Virtual Worlds with Head-mounted Displays, *Non-Holographics True 3-Dimensional Display Technology, SPIE Proceedings*, Vol 1083, Los Angeles CA, January 15-10.

Fisher SS, McGreevy M, Humphries J, Robinett W (1986) Virtual Environment Display System, *Proceeding 1986 Workshop on Interactive 3D Graphics, ACM,* pp.77-87

Foley J, van Dam A, Feiner S, Hughes JF (1990) *Computer Graphics, Principles and Practice*, Second Edition, Addison-Wesley, Reading, MA.

Fuchs H, Poulton J, Eyles J, Greer T, Goldfeather J, Ellsworth D, Molnar S, Turk G, Tebbs B, Israel L, (1989) Pixel-Planes 5: A Heterogeneous Multi-processor Graphics System Using Processor-Enhanced Memory, *Proceedings SIGGRAPH 1989.* Vol 23, No3, ACM Press, pp.79-88.

Furness III TA (1987) Designing in Virtual Space, *Chapter in System Design,* Editors: Rouse W.B., Boff K.R., North-Holland, Amsterdam, pp.127-143.

Ginsberg CM, Maxwell D (1986) Graphical Marionette, *Motion: Representation and Control,* Editors: Badler N.I, Tsotsos J.K, Elsevier Science Publishing, Amsterdam, pp.303-310.

Iwata H (1990) Virtual Reality with Force-feedback: Development of Desktop Virtual Space with Compact Master Manipulator, *Proceeding SIGGRAPH 1990,* Vol 24, No4, pp. 165-170.

Jackoby R (1990) More Virtual Reality Work at NASA Ames, *usenet paper, group sci.virtual-worlds,* Nov.

Jacob RJK (1990) What You Look Is What You Get: Eye Movement-Based Interaction Techniques., *Proceedings CHI conference, 1990, Empowering People*, Seattle Washington, ACM Press, pp 11-18.

Krueger (1983) *Artificial Reality*, Addison-Wesley, Reading, MA.

Luciani A (1990) Physical Models in Animation. Towards a Modular and Instrumental Approach, *Proceedings of Eurographics Workshop on Animation*, Lausanne, Switzerland.

Minsky M, Ouh-young M, Steele O, Brooks Jr FP, Behensky M, (1990) Feeling and Seeing: Issues in Force Display, *Proceedings ACM Siggraph Symposium on Interactive 3D Graphics*, 1990, 24(2), pp 235-243.

Stewart D (1991) Through the Looking Glass into an Artificial World -- Via Computer., *Smithonian Magazine*, Vol.21, No10, pp.36-45.

Studmann DJ, Zeltzer D, Feiner S (1989) Hands-on Interaction with Virtual Environments, *Proceedings of the ACM SIGGRAPH Symposium on User Interface Software and Technology*, Williamsburg, Virginia, Nov. 13-15, ACM Press, pp.19-24.

Sutherland IE (1965) The Ultimate Display, *Proceedings IFIP Congress 1965*

Sutherland IE (1968) A Head-mounted Three Dimensional Display, *1968 Fall Joint Computer Conference, AFIPS Conference Proceedings*, Vol 33, pp.757-764.

Turner R, Balaguer F, Gobbetti E, Thalmann D (1991) Physically-based Interactive Camera Motion Control Using 3D Input Devices, *Proceedings Computer Graphics International 91*, Boston, MA.

Wang J, Chi V, Fuchs H, (1990) A Real-time Optical 3D Tracker For Head-mounted Display Systems, *Proceedings ACM Siggraph Symposium on Interactive 3D Graphics*, 1990, Vol.24, No2, pp.205-215.

Ware C, Jessome DR, (1988) Using the Bat: a six-dimensional mouse for object placement, *IEEE CG&A* Vol 8, No6, pp.65-70.

Ware C, Osborne S, (1990) Exploration and Virtual Camera Control in Virtual Three Dimensional Environment., *Proceedings ACM Siggraph Symposium on Interactive 3D Graphics*, Vol.24, No2, pp.175-183.

Zeltzer D (1990) Task-level Graphical Simulation: Abstraction, Representation, Control, Chapter in*:* Badler NI, Barsky BA, Zeltzer D (editors) *Making them Move. Mechanics, Control, And Animation of Articulated Figures*, Morgan Kaufmann Publishers, San Mateo, CA.

Zimmerman TG, Lanier J, Blanchard C, Bryson S, Harvill Y, (1987) A Hand Gesture Interface Design, *Proceeding CHI'87*, pp.189-192.