Published in Proceedings of Computer Graphics '91, London, Nov. 5-7, 1991, pp. 181-196.

Virtual-Worlds Research at the University of North Carolina at Chapel Hill

October 1991

Richard Holloway
Henry Fuchs
Warren Robinett

Department of Computer Science
University of North Carolina at Chapel Hill
USA

This paper gives a very brief look at the origins of of virtual-worlds research, defines the major challenges in this field, and gives an overview of the current state of virtual-worlds research at the University of North Carolina, work that has been going on for over two decades.

Richard Holloway is a PhD student on the Head-Mounted Display project, which is the central project for virtual-worlds research at UNC. He has written the base software libraries for the project, which are now used by almost all current virtual-worlds applications at UNC. His research project is "X-Ray Vision for Cranio-Facial Reconstruction Planning".

Henry Fuchs is Federico Gil professor of computer science and adjunct professor of radiation oncology who, with Kenan professor Frederick P. Brooks, Jr., leads the HMD project.

Warren Robinett was the Head-Mounted Display project manager from 1989 to 1991, and is currently a senior researcher in the department.

1. Introduction

We trace the origin of virtual-worlds research back to the seminal 1965 IFIP address by Ivan Sutherland, called "The Ultimate Display." In this talk, Sutherland postulated displays so realistic that the viewer would have difficulty differentiating computer-generated (virtual) objects from real ones: "The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal" [Sutherland 65]. Thus, by "virtual world", we mean a system that gives the user a sense of being in an environment other than the one he is in, or of simulated objects being in his environment; a system where the user suspends disbelief and has a feeling of presence.

Not content to merely imagine such systems, Sutherland soon designed, built and demonstrated one such system with a realizable subset of these capabilities [Sutherland 68]. The system consisted of headband with a pair of small CRTs attached to the end of a large instrumented mechanical arm, through which head position and orientation could be determined. Hand position was sensed via a user-held camera grip suspended at the end of three fishing lines whose length was determined by the number of rotations sensed on each of their reels. This subset of the "ultimate" capabilities -- stereo images, head tracking, and hand tracking, remains prevalent even today.

However, with the notable exception of flight training simulators and military applications, research on virtual worlds fell into decline after Sutherland's pioneering work. An indication of this lack of interest is that the major computer graphics textbooks of the 1980s (Newman and Sproull, 2nd edition, 1979; Foley and van Dam, 1982) each devoted only a sentence or two to all of head-mounted displays. Work was quietly proceeding, however, in several places, among them the Air Force's Wright-Patterson AFB [Glines 86], NASA-Ames [Fisher et al 86], MIT's Media Lab [Callahan 83], CAE Electronics [CAE Electronics 86], and UNC Chapel Hill (see bibliography). Worthy of special mention is the work done in the area of flight simulators [Schachter 83], which has produced some of the most convincing virtual worlds to date.

The mid-1980s saw a blossoming of activity spawned by the technological advances in small LCD television screens, image-generation systems, and magnetic tracking systems. These advances brought the cost of the components of a virtual-worlds system down to an affordable level, and the system performance up to the point that one could hope to get real work done.

Media interest in this area has steadily mounted in recent years, and such coverage may give the impression that this technology is mature, and that the major technical problems have been solved. Unfortunately, the major technical problems that Sutherland identified in the late 1960s remain with us today:

1. image generation to each eye has to be achieved at real-time rates;
2. tracking of the head and hand has to be determined in real time and with considerable accuracy;
3. head-gear display devices have to produce high-resolution images and wide-angle views for two eyes;
4. force feedback to simulate even simple objects is very difficult.

This paper surveys the current solutions at UNC Chapel Hill to these major problems and to related other ones.

2. Virtual-Worlds Research at UNC-CH in October 1991

The Department of Computer Science at the University of North Carolina at Chapel Hill has been active in virtual-worlds research for over two decades. This section covers all relevant projects and subprojects that touch on the field of what we call "virtual-worlds research". Our research is aimed squarely at the solving the technical problems listed above; in addition, this section also describes some subprojects (such as audio systems and input devices) which are not major research efforts at UNC, but help in making a complete system.

This paper does not cover all of the virtual-worlds research that has been done at UNC, but there is a fairly complete bibliography of UNC virtual-worlds research at the end of this paper for the interested reader. Some previous work is mentioned to give context for current research.

2.1 Technology Subsystems: Hardware

2.1.1 Image Generation: Pixel-Planes

As discussed previously, one of the hardest problems in this field is that of real-time image generation. The Pixel-Planes project started in 1980 with the idea of using a massively parallel architecture for real-time rendering of complex, polygonally-based models in real time. Since then, the project has designed and built five generations of custom IC designs, two small prototypes (Pixel-Planes 2 and 3) and two full-sized systems (Pixel-Planes 4 and 5) which are still in use.

Pixel-Planes 5 is a message-passing multicomputer (see Figure 1) which divides the image generation task among approximately 40 Intel i860-based *graphics processors* (for geometric transformations and other calculations) and approximately 25 renderers (massively parallel arrays of tiny processors based on custom chips that perform most pixel-oriented calculations). Pixel-Planes 5 can render over 2 million Phong-shaded, z-buffered polygons per second at 1280x1024 resolution. It was first used with the head-mounted display system in early 1991, and has substantially enhanced the virtual-worlds applications at UNC, in image realism, complexity, and speed.

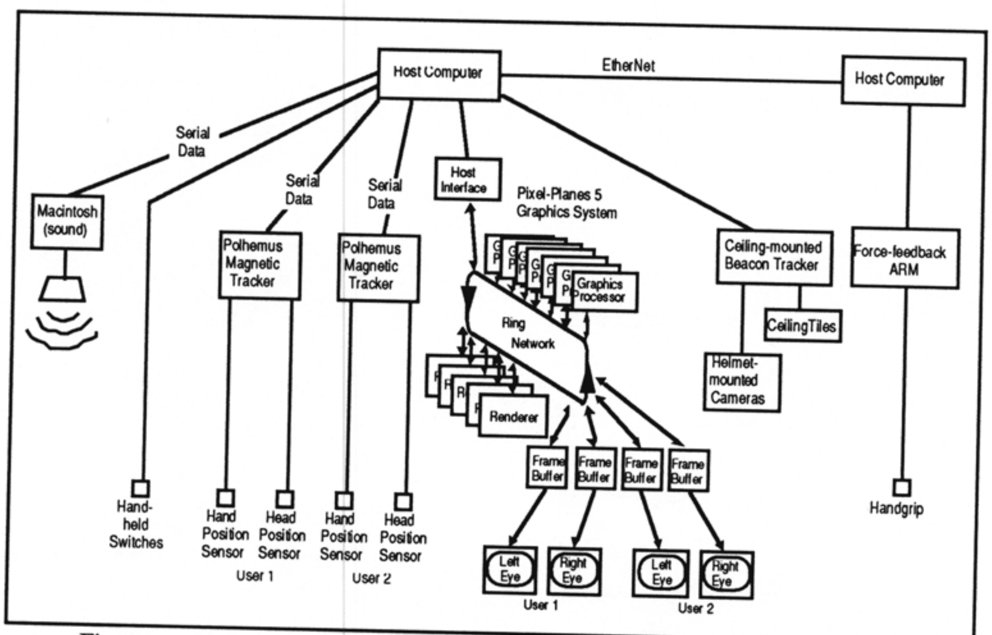

Figure 1 Overview of UNC HMD (Virtual Worlds) System October 1991

2.1.2 Tracking

Researchers now at UNC have been investigating the tracking problem for decades [Fuchs et al 77; Bishop and Fuchs 84]. Our current tracking systems include both commercial systems and systems developed at UNC. A description of each follows.

Commercial Systems

In 1985, we bought a Polhemus 3SPACE magnetic tracker for use with the first see-through HMD. Since then, we have acquired two additional units, plus an Ascension Bird magnetic tracker. These magnetic systems currently have uncomfortably long latency[1] which limits the real-time system response, and limited range, which constrains the user to a working volume of only a few cubic meters.

The UNC Ceiling Tracker

In an attempt to address the limitations of current magnetic systems, Jih-Fang Wang [Wang 90] designed an optical tracking system using an "inside-out" paradigm pioneered by Bishop [Bishop 84]. In this system, cameras are mounted on the user's head and monitor the relative positions and orientations of infrared LED beacons mounted in the ceiling. From information about three or more beacons, the position and orientation of the cameras (and thus the user's head) can be derived.

Wang designed and constructed a benchtop prototype system which was finished in March of 1990. The system was largely reworked by our tracker research group in building a full-scale ceiling tracker, which was completed in July of 1991 and demonstrated at SIGGRAPH '91. The ceiling uses two-foot-square tiles that in principle can be put in place of ordinary ceiling tiles in a suspended ceiling framework. The ceiling area is 10 feet by 12 feet at present, which is a considerably larger working volume than that of any trackers known to us. The update rate varies depending on how many LEDs are visible, but the maximum rate is currently around 100 frames per second, with two frames of latency. Work on improving the system continues, including combining the ceiling with a magnetic tracker for tracking the user's hand.

2.1.3 Head-Mounted Displays

As with the tracking systems cited above, we use both commercially available systems and "home-grown" systems for our head-mounted displays (HMDs). UNC's work in this area dates back to the early eighties (see history in [Chung et al 89]). Generally speaking, head-mounted displays can be divided into two categories: "see-through" (the computer image is superimposed onto the real world) and opaque (the real world view is blocked by the apparatus). Each type has its own uses and advantages, depending on the application for which it is used.

Commercial Systems

Currently, the HMDs that we use most are made by VPL- we have two regular EyePhones (Model 2's) plus another EyePhone Model 2 which was specially modified to hold the special cameras for the ceiling tracker. All of these models are opaque, and use color LCD screens and LEEP wide-angle optics.

---

[1] The delay between the time the user moves and the time that movement is reported by the tracker.

UNC See-Through HMDs

We are particularly interested in see-through HMDs because they allow computer-generated images to be superimposed on the real world, which allows the system to *enhance* reality, rather than supplant it. An example of this is the "X-ray vision" application described in section 2.3.4.

In 1986, there were no reasonably priced, commercially available HMDs, so we built our own simple, black-and-white, see-through unit using commercially available LCD screens and half-silvered mirrors. A color version followed in 1987. These models were usable, but suffered from poor image quality and lack of durability.

All of the LCD-based HMDs that we have used suffer from the problem of poor resolution, which leads to grainy, pixelated images[2]. At UNC, Warren Robinett and Jannick Rolland carried out an informal experiment using a virtual Snellen eye chart which showed that a user wearing a VPL EyePhone Model 1 is legally blind, having approximately 20/250 vision. To address this problem, and because we are interested in see-through capability, we are currently building a new see-through HMD using tiny CRTs[3] instead of LCDs. The system under construction will have custom-designed optics with a 60-degree field-of-view for each eye.

2.1.4 Force Feedback

Research into force feedback at UNC dates back to 1967, when the GROPE I project work used a 2D force-feedback device to enhance understanding of continuous 2D force fields [Batter and Brooks 71].

The main hardware component of subsequent work has been a 6-D force-feedback arm, donated to us by Argonne National Laboratories. The ARM (Argonne Remote Manipulator) can output three forces and three torques at the handgrip where the user holds it, and has a working volume of about one cubic meter. This allows it to simulate a wide variety of virtual forces over a fairly large working volume. This capability has been explored by three different studies: grasping and manipulating of virtual blocks on and over a virtual table [Kilpatrick 76], finding the minimum-energy position and orientation of a virtual bar suspended by springs [Ouh-Young 90], and finding a minimum energy docking configuration for drugs in the active site of a protein molecule [Ouh-Young, Beard and Brooks 90]. A summary of this work is given in [Brooks et al 90].

A much simpler force feedback system was implemented for the virtual mountain bike application. Here, a CompuTrainer eddy-current brake is connected to the rear wheel of the mountain bike (described in section 2.1.6) and controlled by the host computer via a serial line to give force feedback to the rider. When the application detects that the user is going up a hill, it sets the CompuTrainer to a higher braking value to make pedaling more difficult.

2.1.5 Audio

Audio systems have long been in use at UNC for both output (i.e., computer-controlled sounds) and input (i.e., speech recognition). While not a major research effort at UNC, the audio systems have been a useful addition to the virtual-worlds systems developed here.

---

[2] The resolution of the EyePhone Model 2 is listed as 360x240 in primary-color pixels; this gives something like 208x139 resolution for RGB triads. VPL's EyePhone HRX has approximately 416x277 RGB-triad resolution (the VPL literature lists it as 720x480 primary colored pixels), which is still lower resolution than a standard NTSC video signal, and much less than a 1280x1024 workstation screen.

[3] Current CRT technology affords 1000x1000 resolution for a one-inch-square display.

Audio Output: Kirkpatrick's force feedback work with virtual blocks used an audible click to signal contact between virtual objects. We now have a dedicated Macintosh IIci sound server for virtual worlds applications which is used by many applications. The Macintosh is connected to the host via a serial line, and plays prerecorded sounds under application control. In addition, a CD-ROM player with an extensive sound effects library is connected to the Mac which gives application programs over 1,000 sounds to choose from.

Audio Input: In the mid-1980s, the GRIP project used a Votan speech recognizer with the GRINCH system. More recently, we have acquired a DragonWriter speech recognition system for our lab which has been used with some applications. The accuracy of speech recognition systems is still a significant limitation for multi-user systems.

2.1.6 Input Devices

One of the most interesting parts of virtual worlds applications is the equipment used to get user input to the system. Like the audio subsystems, this is not a major research effort, but is a necessary part of a complete system. A list of the most important devices follows.

Manual Input Devices

Pool Ball - The most common input device in our labs is currently a hollowed-out billiard ball with a Polhemus sensor placed inside of it, and two buttons on the outside of it. This device has served us well since 1986 [Brooks 86], and lends itself well to all sorts of applications. We find it easier to use and more precise than the DataGlove (described below), which is used at many other sites as the primary input device. The advantages of the pool ball are that it does not require calibration for each user, its position can be accurately specified at all times, and actions initiated with the buttons are easy to control precisely.

Finger Pick- This is a variation on the pool ball and consists of a guitar finger pick on which is mounted a Polhemus sensor and a small microswitch. This device is simple, intuitive for grabbing, and does not have to be held.

Joybox- An old favorite in our lab for analog input is the joybox, which is a pair of three-degree-of-freedom joysticks with a slider.

DataGlove- Our VPL DataGlove has been used for some applications, but in general, it has more degrees of freedom than most applications need or want. The glove gives information about the angle for all of the user's hand joints, which the application usually has to compress into some small number of *gestures*. Our experience has been that it is usually simpler to encode the gestures using the buttons on the pool ball.

Navigation Devices

Steerable Treadmill- This device addresses the need to virtually walk through virtual environments that are larger than the range of the tracker. A modified treadmill is used to measure how far the user has walked on it so that that information can be reflected in the virtual world. A set of bicycle handlebars mounted on the front allows the user to change direction, and shaft encoders detect the rate of rotation of both the handlebars and the treadmill itself.

Bicycle- Another means of exploring a large virtual world is with a virtual mountain bike. This device consists of a regular mountain bike mounted on a stand, with shaft encoders to detect how fast the rear wheel is spinning and what the current handlebar direction is. As described above, an eddy-current brake on the rear wheel provides force feedback to enhance the realism of this simulation.

2.2 Technology Subsystems: Software

The guiding principle behind the software effort for all of these projects has been device-independence. The devices described above are being modified constantly as technology improves, and thus there must be a layer of software in between the drivers and the applications to shield the applications from low-level changes in the drivers. To that end, a suite of libraries in C has been developed for applications programmers. Generally speaking, application programmers can think in terms of abstract notions such as *displays*, *trackers*, and *input devices*, rather than "EyePhone Model 1", "Polhemus 3SPACE", etc. Application programs can choose at run-time which display, tracker and input device they wish to use, simply by changing the value of a Unix environment variable. The libraries handle the interface so that switching between devices is easy, and changes to the devices themselves do not affect the application code. An interconnection diagram and a brief description of the libraries follows.

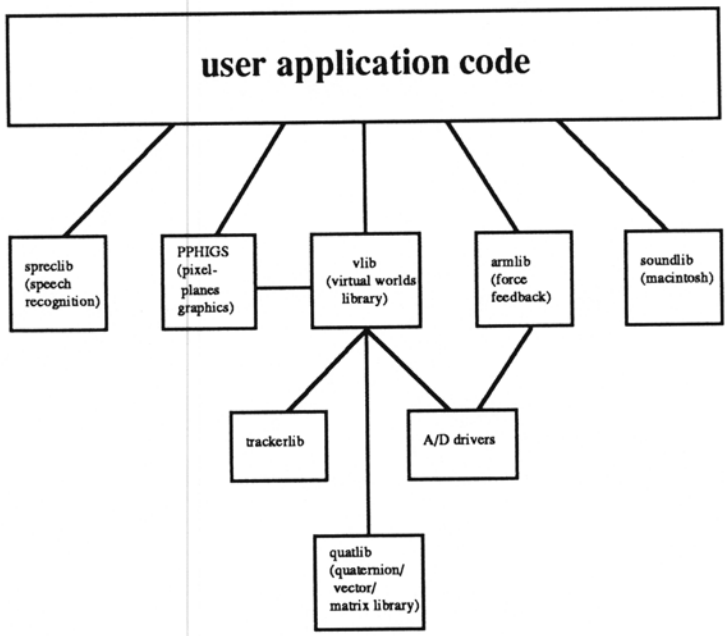

Figure 2 Overview of UNC Virtual-Worlds Software

Vlib provides a software layer that makes all of the UNC HMDs look logically the same so that applications can switch between them easily. It also provides support for coordinate systems, transformations, and routines for doing common virtual-world operations, such as flying, grabbing, and scaling [Robinett and Holloway 91].

PPHIGS is a local version of the PHIGS+ graphics standard. Applications call both vlib and PPHIGS in order to build virtual worlds and interact with them.

Trackerlib provides a uniform software layer over all of our current trackers so that applications can access all of them interchangeably.

Armlib hides the low-level details of the ARM's driver and also allows applications to use the ARM from remotely connected machines.

Soundlib is the software library that runs on the Unix host and communicates with the Macintosh sound server software.

Spreclib is the speech-recognition library and runs on a dedicated IBM-PC speech-recognition server.

ADlib provides a high-level interface to applications to shield them from specific dependencies on input devices.

2.3 Applications

While the pursuit of virtual worlds technology is interesting and challenging in and of itself, the emphasis at UNC is on improving the technology by tackling real-world applications and letting their problems drive the research. Our belief is that working on real-world applications forces us to solve all the problems in a system, not just the easy ones.

What follows is a list of virtual worlds applications in progress at UNC; the more mature applications are listed first.

2.3.1 GRIP: Molecular Studies

The GRIP project started in 1968 with the goal of advancing research in computer graphics by building tools for biochemists. The subprojects of GRIP related to this paper are:

GROPE I, II, and III - Force feedback research described in section 2.1.4.

Flying Through Molecules- Biochemists can load in a protein molecule modeled as a network of rods or a cluster of spheres, put on the head-mounted display, and enter a world where angstroms are as long as meters, and atoms are as big as beach balls. The user can grab the molecule, scale it up and down, and fly through it.

Trailblazer- This new system uses a large mirror and a CRT with stereo glasses to make a molecular model seem to float in space near the biochemist's hand. The biochemist can reach out using the finger-pick device (described in section 2.1.6) to grab a virtual molecular bond and move it around. The rest of the molecule flexes to compensate for the changes induced by the user according to physical laws.

2.3.2 Walkthrough

The Walkthrough project started in 1985 with the basic goal of "a virtual building environment, a system which simulates human experience with a building, without physically constructing the building" [Airey, Rohlf and Brooks 90]. Using this system, the user can "walk through" in real time a building that may not yet exist. As the user moves through the three-dimensional building model, perspective views are generated using the radiosity lighting model that make it seem as if the user is really inside the building.

Viewing can be done with a regular CRT, the large rear-projection screen, or a head-mounted display. The user can move through the building by walking under the ceiling tracker or on the treadmill, or by steering with a joybox.

This system was used to walk through the UNC computer science building before it was built and was used to make some design modifications before the construction began.

2.3.3 Radiation Treatment Planning

There is currently a large research effort at UNC in employing computer graphics techniques in the area of radiation oncology [Rosenman et al 89]. In addition, James Chung is working on a CAD tool using a head-mounted display for designing radiotherapy treatment beam configurations in the hopes that it will aid radiotherapists in making better treatment plans.

In this system, a model of the patient's anatomy is explored by a physician who is preparing a radiation therapy treatment plan in order to deliver a lethal dose of radiation to a tumor, while minimizing the exposure of healthy tissue to the radiation. The physician puts on a head-mounted display and walks around a model of the patient's anatomy (as obtained by standard computed tomography (CT) methods and rendered as a set of polygons) and some number of polygonally defined radiation beams. The physician experiments with different beam placements by "grabbing" the virtual beam with the 3D mouse in order to find an acceptable placement of the beams as described above.

The problem that this system addresses is that currently, radiation treatment planners have to look at the patient's anatomy on a two-dimensional screen, which makes it difficult to understand views other than the "cardinal" (orthogonal) views, so treatment geometries involving odd angles are not often used, even though they might result in a better overall treatment. The projected advantage of this system is that in the virtual world, the physician is free to examine all angles of beam placement in a natural manner, and should thus allow better treatment plans in less time.

2.3.4 X-Ray Vision

X-Ray Vision is a planned head-mounted display application where, instead of blocking out the view of the real world in favor of the computer-generated world, the computer-generated world is superimposed on the real world, using the aforementioned see-through head-mounted display.

The images to be superimposed can come from CT, MR (magnetic resonance), ultrasound, or any other imaging technique. Richard Holloway's research is superimposing static 3D reconstructions of CT or MR images (as opposed to scanning in real-time) onto a real patient. This would allow the surgeon planning reconstructive surgery to see the real soft tissue, yet have a three-dimensional image of the underlying bone at the same time.

2.3.5 Non-Research Applications

In addition to applications that are designed to solve real-world problems, there are many, smaller projects that have been done in order to explore the possibilities of virtual worlds. Many of the following projects came from the biennial course "Exploring Virtual Worlds" at UNC. The lessons learned in the creation of these applications have benefitted the research applications as well. A brief summary of a few of these projects follows.

Adventure Game- In a network of rooms connected by portals, the user can see himself in a virtual mirror, use a "vortex gun" to shoot a giant virtual bird, and take a ride in a virtual elevator. *Credits: Warren Robinett.*

Carnival- This application featured an amusement park including a train, a ferris wheel, a merry-go-round, and an elevator. *Credits: Erik Erikson*

City and Lake Flythrough- The user can fly between buildings in a virtual city and through targets that give directions on where to go next. Collisions are detected and audio and force feedback make the user aware of the collision. In the lake, the user swims with fish that are animated in such a way that they avoid collisions with each other and objects in the lake. *Credits: Ron Azuma, Ulrich Neumann.*

Mountain Bike- The user can ride through a countryside complete with trees, traffic lights, barn, water tower, animated birds, Burma Shave road signs, and pylons that he can run over. *Credits: Erik Erikson, Ryutarou Ohbuchi, Russ Taylor.*

Solar System- Our solar system is modeled to scale; the user can fly between planets and moons, change his frame of reference and orbit on a different planet, and scale the world up and down. *Credits: Warren Robinett.*

3D Modeler- Like MacDraw in 3D. The user can create his own geometric models interactively, out of such primitives as blocks, spheroids, and extruded curves. The system allows two independent users: a designer and an observer/client. *Credits: Drew Davidson, Jeff Butterworth, Marc Olano, Steve Hench.*

Virtual Dog- As a test of the speech recognition subsystem, a virtual dog was created to respond to user commands. The virtual dog knew how to speak, come, jump, and roll over. *Credits: Bill Brown*

Virtual Piano- When the user puts on the DataGlove and presses a key on the virtual eleven-key keyboard with his virtual hand, the key descends and a note is played by the Macintosh, corresponding to the key that was pressed. *Credits: Bill Brown*

Virtual Pilot- A minimalist flight simulator. The user flies over a textured landscape of land or sea and controls the flight direction by accelerating or decelerating in the direction he is looking. The land simulation includes an independently flying 747, and the sea environment has an aircraft carrier. *Credits: Trey Greer (working for Ivex Corporation)*

Virtual Golf- The user is armed with a special putter (whose movement is tracked by the system) in order to sink a virtual golf ball into a virtual cup. When the user sinks the putt, the flag sticking out of the hole turns red and the sound of a ball falling into a cup is played.
Credits: Curtis Hill

3. Conclusion

These are times of great change in virtual worlds research. This is a far cry from the situation of even five years ago, when much of a system had to be custom-built. The technology is sufficiently well-developed now that commercial offerings are available for all of the system components, making it possible for groups without hardware-development capabilities to conduct virtual-worlds research. Although the demands of many applications still exceed the capabilities of the technology, it is encouraging that at least a few applications are ready for end users.

Now, even more difficult and subtle challenges may lie ahead; some of the problems we are currently facing are:

- low image quality of LCDs
- expense and availability of tiny CRT systems
- eliminating the lag between user motion and system response
- wide field of view in stereo that is superimposed on the view of the real world
- superimposing virtual objects on the real world in a way that makes sense to the human visual system
- comfort vs. encumbrance virtual-worlds head and body gear
- performance of non-real-time operating systems
- modeling complex virtual worlds
- image generation for complex scenes

If we can't overcome these problems, virtual worlds may continue to be limited to a few specialized applications (flight simulation and entertainment, for example). If we *can* solve these problems, then we may look back in twenty years and consider these last few years as the time when human-computer interaction left the confines of the desktop computer screen and merged with the 3D world of the user. If so, today's futuristic virtual worlds applications will seem to their users in twenty years as mundane as today's WYSIWYG "virtual paper" displays appear to today's desk-top publishers.

4. Credits

Image Generation: Pixel-Planes

PIs: Henry Fuchs, John Poulton *Software Manager:* Anselmo Lastra

Current: Mike Bajura, Andrew Bell, Jeff Butterworth, David Ellsworth, John Eyles, Trey Greer (working for Ivex Corporation), David Harrison, Chip Hill, Vicki Interrante, Jonathan Leech, Steve Molnar, Ulrich Neumann, Marc Olano, John Rhoades, Greg Turk, Sharon Walters, Laura Weaver

Former: John Austin, Howard Good, Edward Hill, Brice Tebbs, Russ Tuck

Tracking

PI: Henry Fuchs

Current: Ron Azuma, Brad Bennett, Gary Bishop, Vern Chi, Stefan Gottschalk, Phil Jacobsen, Mark Mine

Former: Jack Kite, Jih-Fang Wang, Mark Ward

Head-Mounted Displays

PIs: Frederick Brooks, Jr. and Henry Fuchs

Current: Gary Bishop, Jim Chung, Drew Davidson, Erik Erikson, David Harrison, Rich Holloway, Doug Holmgren, John Hughes, Steve Pizer, Jannick Rolland, Russ Taylor,

Former: Warren Robinett, Mark Harris, Project Managers
Bill Brown, C. Cheung, Brad Crittenden, Mike Kelley, Ming Ouh-Young, Mike Pique

Force Feedback

(Most of the force feedback research has been done as part of the GRIP project.)

Current: Jeff Chen, Erik Erikson, John Hughes, Ryutarou Ohbuchi, Russ Taylor, William Wright

Former: James Batter, Jerome Kilpatrick, Margaret Minsky, Ming Ouh-Young, Mike Pique, Neela Srinivasan

Audio

(Most of the audio research has been done as part of the HMD and Walkthrough projects.)

Current: Drew Davidson, John Hughes, Warren Robinett, Xialin Yuan

Former: Bill Brown

Input Devices

(Most of the input device research has been done as part of the HMD, Walkthrough and GRIP projects.)

Current: Jim Chung, Drew Davidson, Erik Erikson, David Harrison, Rich Holloway, John Hughes, Warren Robinett, Russ Taylor

Former: Jack Kite, Phil Stancil

GRIP: Molecular Studies

(The following lists only the project members and collaborators whose work touched on a virtual-worlds application; the list of all project members and collaborators is much longer.)

PI: Frederick P. Brooks, Jr.

Current : William Wright, Project Director / Research Professor
Jeff Chen, Jim Chung, Richard Holloway, John Hughes, David and Jane Richardson, Russ Taylor, Mark Surles

Former : Project Directors: Mike Pique, Helga Thorvaldsdottir, Mark Harris, Warren Robinett
James J. Batter, David Bennett, Bill Brown, Joe Capowski, P. Jerome Kilpatrick, Ming Ouh-Young

Walkthrough

PI: Frederick P. Brooks, Jr

Current: John Alspaugh, John Hughes, Amitabh Varshney, Yulan Wang, Xialin Yuan

Former: John Airey, Randy Brown, Curtis Hill, John Rohlf, Douglass Turner

Radiation Treatment Planning

(part of the Head-Mounted Display Project)

Current: James Chung, Stephen Pizer, Julian Rosenman

X-Ray Vision

(part of the Head-Mounted Display Project)

Current: Gary Bishop, Jefferson Davis, Richard Holloway, Doug Holmgren, John Hughes, Warren Robinett, Jannick Rolland

5. Acknowledgements

The work described in this paper has been supported by one or more of the following grants:

Defense Advanced Research Projects Agency, Contract No. DAEA 18-90-C-0044: "Advanced Technology for Portable Personal Visualization" (F.P. Brooks, Jr., and Henry Fuchs, principal investigators) This paper approved for public release. Distribution unlimited.

Digital Equipment Corporation, Research Agreement No. 582: "Interactive 3D Computer Graphics Systems and Applications" (Henry Fuchs, principal investigator)

National Institutes of Health, National Center for Research Resources, Grant No. 5-R24-RR-02170: "Interactive Graphics for Molecular Studies" (Frederick P. Brooks, Jr., principal investigator)

National Institutes of Health, Grant No. P01 CA47982: "Program Project Grant on Medical Image Presentation" (Stephen M. Pizer, program director; especially the "Three Dimensional Medical Image Display" section, Henry Fuchs, principal investigator)

National Science Foundation, Grant No. CDA-8722752, "CISE Institutional Infrastructure Program for Prototyping Complete Digital Systems" (Vernon Chi, Susanna Schwab, and Stephen Weiss, principal investigators)

National Science Foundation, Grant No. MIP-9000894, and Defense Advanced Research Projects Agency, Order No. 7510: "Supercomputing Power for Interactive Visualization" (Henry Fuchs and John Poulton, principal investigators)

National Science Foundation, Cooperative Agreement No. ASC-8920219, and Defense Advanced Research Projects Agency: "Science and Technology Center for Computer Graphics and Scientific Visualization" (Donald Greenberg, center director, Principal investigators at the five participating institutions are: Andries van Dam, Brown University; Alan Barr, California Institute of Technology; Donald Greenberg, Cornell University; Henry Fuchs, University of North Carolina at Chapel Hill; Richard Riesenfeld, University of Utah)

National Science Foundation, Grant No. CCR 8609588, "Walkthrough - A Dynamic Graphics System for Simulating Virtual Buildings" (Frederick P. Brooks, Jr., principal investigator)

Office of Naval Research, Grant No. N00014-86-K-0680: "The Infrastructure of Command Information Systems" (Stephen Weiss, Frederick P. Brooks, Jr., and Donald Stanat, principal investigators)

6. Bibliography

6.1 Cited References for Work Done Elsewhere

CAE Electronics, Ltd. 1986. Introducing the visual display system you wear. Quebec. 4pp.

Callahan, M.A. 1983. A 3-D display head-set for personalized computing. MS thesis. Department of Architecture. Massachussetts Institute of Technology.

Fisher, S.S, M. McGreevy, J. Humphries, and W. Robinett. 1986. Virtual environment display system. *ACM Proceedings of the 1986 Workshop on Interactive 3D Graphics.* 77-87.

Fuchs, Henry, Joe Duran and Brian Johnson. 1977. A system for automatic acquisition of three-dimensional data. In *Proceedings of the 1977 National Computer Conference.* 46:49-53.

Glines, C.V. 1986. Brain buckets. *Air Force Magazine.* 69:8:86-90.

Rheingold, Howard. 1991. *Virtual Reality.* New York. Summit.

Schachter, B. 1983. *Computer Image Generation.* New York. Wiley.

Sutherland, Ivan. 1965. The ultimate display. *Information Processing 1965: Proceedings of IFIP Congress 65.* 506-508.

Sutherland, Ivan. 1968. A head-mounted three-dimensional display. *Proceedings of the 1968 Fall Joint Computer Conference.* Thompson Books. 757-764.

6.2 Work Done at UNC

Architectural Walkthrough

Airey, John, John Rohlf, and Frederick P. Brooks, Jr. 1990. Towards image realism with interactive update rates in complex virtual building environments. *Computer Graphics: Proceedings of 1990 Symposium on Interactive 3D Graphics.* Snowbird, Utah. 41-50.

Brooks, Frederick P., Jr. 1986. Walkthrough—A dynamic graphics system for simulating virtual buildings. In *Proceedings of 1986 Workshop on Interactive 3D Graphics.* UNC-Chapel Hill. 9-21.

Force Feedback

Batter, J.J. and F.P. Brooks, Jr. 1971. GROPE-I: A computer display to the sense of feel. In *Information Processing: Proceedings of IFIP Congress 71.* 759-763.

Brooks, F.P., Jr., M. Ouh-Young, J.J. Batter, and P.J. Kilpatrick. 1990. Project GROPE—Haptic displays for scientific visualization. *Computer Graphics: Proceedings of SIGGRAPH '90.* Dallas,TX. 177-185.

Capowski, J.J. 1971. Remote manipulators as a computer input device. MS thesis. University of North Carolina, Chapel Hill.

Kilpatrick, P.J. 1976. The use of kinesthetic supplement in an interactive graphics system. PhD dissertation. University of North Carolina, Chapel Hill.

Minsky, Margaret, Panel Chair. 1989. Recent progress creating environments with the sense of feel: Giving look and feel its missing meaning. *Proceedings of CHI '89.* Austin, TX. F.P. Brooks, Jr., M. Behensky, D. Milliken, M. Russo and A. Druin, panelists.

Minsky, Margaret, Ming Ouh-Young, Oliver Steele, Frederick P. Brooks, Jr., and Max Behensky. 1990. Feeling and seeing: Issues in force display. *Computer Graphics: Proceedings of 1990 Symposium on Interactive 3D Graphics.* Snowbird, Utah. 235-244.

Ouh-Young, Ming. 1990. Force display in molecular docking. PhD dissertation. University of North Carolina, Chapel Hill.

Ouh-Young, Ming, D.V. Beard and F.P. Brooks, Jr. 1989. Force display performs better than visual display in a simple 6-D docking task. *Proceedings of IEEE 1989 Robotics and Automation Conference.* Scottsdale, AZ. 3:1462-1466.

Ouh-Young, Ming, M. Pique, M. Harris, J. Hughes, N. Srinivasan and F.P. Brooks, Jr. 1988. Force display in molecular docking. Abstract in *Journal of Molecular Graphics.* 6:4:224.

Ouh-Young, Ming, M. Pique, J. Hughes, N. Srinivasan and F.P. Brooks, Jr. 1988. Using a manipulator for force display in molecular docking. *Proceedings of IEEE 1988 Robotics and Automation Conference.* Philadelphia, Pennsylvania. 3:1824-1829.

Steelman, H.S. 1968. The GROPE-I system: An analysis of friction and backlash problems. MS thesis. University of North Carolina, Chapel Hill.

Head-Mounted Display

Brooks, Frederick P. Jr. 1988. Grasping reality through illusion. *Proceedings of CHI '88.* Washington, D.C.

Chung, J.C., M.R. Harris, F.P. Brooks, Jr., H. Fuchs, M.T. Kelley, J. Hughes, M. Ouh-Young, C. Cheung, R.L. Holloway and M. Pique. 1989. Exploring virtual worlds with head-mounted displays. *Non-Holographic True 3-Dimensional Display Technologies: SPIE Proceedings*. Los Angeles, CA. 1083:15-20.

Holloway, R.L. 1987. Head-mounted display. UNC technical report.

Lipscomb, J.S. 1987. Comparison of stereoscopic display devices at the University of North Carolina at Chapel Hill. *Chemical Design Automation News*. 2:5:3-6.

Robinett, Warren, and Jannick Rolland. 1991. A computational model for the stereoscopic optics of a head-mounted display. To appear in *Presence. 1:1*.

Robinett, Warren. 1991. Electronic expansion of human perception. *Whole Earth Review*. 16-21.

Robinett, Warren, and Richard Holloway. 1991. Flying, grabbing and scaling in virtual reality. Submitted for publication.

Medical Imaging

Levoy, Marc, and Ross Whitaker. 1990. Gaze-directed volume rendering. *Computer Graphics: Proceedings of 1990 Symposium on Interactive 3D Graphics*. Snowbird, Utah. 24:2:217-224.

Mills, Peter H., Henry Fuchs. 1990. 3D ultrasound display using optical tracking. *Proceedings of the First Conference on Visualization in Biomedical Computing*. Atlanta, GA. 490-497.

Ohbuchi, Ryutarou and Henry Fuchs. 1990. Incremental 3D ultrasound imaging from a 2D scanner. *Proceedings of the First Conference on Visualization in Biomedical Computing*. Atlanta, GA. 360-367.

Ohbuchi, Ryutarou, and Henry Fuchs. 1991. Incremental volume rendering algorithm for interactive 3D ultrasound imaging. *Proceedings of the Information Processing in Medical Imaging (IPMI) Conference XII*. 486-500.

Rosenman, Julian, George W. Sherouse, Henry Fuchs, Stephen M. Pizer, Andrew L. Skinner, Charles Mosher, Kevin Novins and Joel E. Tepper. 1989. Three-dimensional display techniques in radiation therapy treatment planning. *Int. J. Radiation Oncology Biol. Phys.* 16:1.

Pixel-Planes

Eyles, J., J. Austin, H. Fuchs, T. Greer and J. Poulton. Pixel-Planes 4: A summary. *Proceedings of the Eurographics '87 Second Workshop on Graphics Hardware: Advances in Computer Graphics Hardware II*. 183-208.

Fuchs, H., J. Goldfeather, J.P. Hultquist, S. Spach, J.D. Austin, F.P. Brooks, Jr., J.G. Eyles and J. Poulton. 1985. Fast spheres, shadows, textures, transparencies, and image enhancements in Pixel-Planes. *Computer Graphics: SIGGRAPH '85 Conference Proceedings*. 19:3:111-120. Reprinted in *Advances in Computer Graphics I*. G. Enderle, M. Grave, and F. Lillehagen, eds. Springer-Verlag. 1986. 169-187. Also reprinted in *Tutorial: Computer Graphics Hardware—Image Generation and Display*. Hassan K. Reghbati and Anson Y.C. Lee, eds. IEEE Computer Society Press. 1988. 222-231.

Fuchs, Henry, John Poulton, John Eyles, Trey Greer, Jack Goldfeather, David Ellsworth, Steve Molnar, Greg Turk, Brice Tebbs and Laura Israel. 1989. A heterogeneous multiprocessor graphics system using processor-enhanced memories. *Computer Graphics: Proceedings of SIGGRAPH '89*. 23:4:79-88.

Tracking

Bishop, Gary. 1984. Self-tracker: A smart optical sensor on silicon. PhD dissertation. University of North Carolina, Chapel Hill.

Bishop, Gary, and Henry Fuchs. 1984. The self-tracker: A smart optical sensor on silicon. *Proceedings of the 1984 MIT Conference on Advanced Research in VLSI*. Dedham, MA. Artech House. 65-73.

Wang, J., R. Azuma, G. Bishop, V. Chi, J. Eyles, and H. Fuchs. 1990. Tracking a head-mounted display in a room-sized environment with head-mounted cameras. *Proceedings: SPIE '90 Technical Symposium on Optical Engineering & Photonics in Aerospace Sensing*. Orlando, FL.

Wang, J., V. Chi and H. Fuchs. 1990. A real-time optical 3D tracker for head-mounted display systems. *Computer Graphics: 1990 Symposium on Interactive 3D Graphics*. 24:2:205-215.

Wang, Jih-Fang. 1990. A real-time optical 6D tracker for head-mounted display systems. PhD dissertation. University of North Carolina, Chapel Hill.