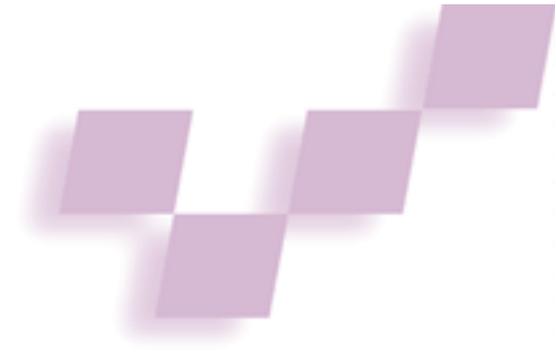


What's Real About Virtual Reality?



Frederick P. Brooks, Jr.
University of North Carolina at Chapel Hill

As usual with infant technologies, realizing the early dreams for virtual reality (VR) and harnessing it to real work has taken longer than the initial wild hype predicted. Now, finally, it's happening.

In his great invited lecture in 1965, "The Ultimate Display," Ivan Sutherland laid out a vision¹ (see the sidebar), which I paraphrase:

Don't think of that thing as a *screen*, think of it as a *window*, a window through which one looks into a *virtual world*. The challenge to computer graphics is to make that virtual world look real, sound real, move and respond to interaction in real time, and even feel real.

This personal assessment of the state of the VR art concludes that whereas VR almost worked in 1994, it now really works. Real users routinely use production applications.

This research program has driven the field ever since.

What is VR? For better or worse, the label *virtual reality* stuck to this particular branch of computer graphics. I define a *virtual reality experience* as any in which the user is effectively immersed in a responsive virtual world. This implies user dynamic control of viewpoint.

VR almost worked in 1994.

In 1994, I surveyed the field of VR in a lecture that asked, "Is There Any Real Virtue in Virtual Reality?"² My assessment then was that VR almost worked—that our discipline stood on Mount Pisgah looking into the Promised Land, but that we were not yet there. There were lots of demos and pilot systems, but except for vehicle simulators and entertainment applications, VR was not yet in production use doing real work.

Net assessment—VR now barely works. This year I was invited to do an up-to-date assessment of VR, with funding to visit major centers in North America and

Europe. Every one of the component technologies has made big strides. Moreover, I found that there now exist some VR applications routinely operated for the results they produce. As best I can determine, there were more than 10 and fewer than 100 such installations as of March 1999; this count again excludes vehicle simulators and entertainment applications. I think our technology has crossed over the pass—VR that used to *almost work* now *barely works*. VR is now really real.

Why the exclusions? In the technology comparison between 1994 and 1999, I exclude vehicle simulators and entertainment VR applications for different reasons.

Vehicle simulators were developed much earlier and independently of the VR vision. Although they today provide the best VR experiences available, that excellence did not arise from the development of VR technologies nor does it represent the state of VR in general, because of specialized properties of the application.

Entertainment I exclude for two other reasons. First, in entertainment the VR experience itself is the result sought rather than the insight or fruit resulting from the experience. Second, because entertainment exploits Coleridge's "willing suspension of disbelief,"³ the fidelity demands are much lower than in other VR applications.

Technologies

Four technologies are crucial for VR:^{4,5}

- the visual (and aural and haptic) displays that immerse the user in the virtual world and that block out contradictory sensory impressions from the real world;
- the graphics rendering system that generates, at 20 to 30 frames per second, the ever-changing images;
- the tracking system that continually reports the position and orientation of the user's head and limbs; and
- the database construction and maintenance system for building and maintaining detailed and realistic models of the virtual world.

Four auxiliary technologies are important, but not nearly so crucial:

- synthesized sound, displayed to the ears, including directional sound and simulated sound fields;
- display of synthesized forces and other haptic sensations to the kinesthetic senses;
- devices, such as tracked gloves with pushbuttons, by which the user specifies interactions with virtual objects; and
- interaction techniques that substitute for the real interactions possible with the physical world.

Table 1 summarizes the technology progress since 1994.

Displays

Display technology has advanced very rapidly, pulled along by the television, presentation-projection, and LCD-device markets, rather than just the still-small VR market. As VR was developing, much ink was spilled over the relative merits of various formats of displays: head-mounted displays (HMDs), CAVE-like (Cave Automatic Virtual Environment) surround projectors, panoramic projectors, workbench projectors, and desktop displays.

Most workers consider desktop displays not to be VR because they

- hardly block out the real world,
- do not present virtual-world objects in life size, and therefore
- do not create the illusion of immersion.

To be sure, one could say the same for workbenches, but somehow the result is not at all the same. Workbenches were originally designed for human-body models, which they do display life-size. Moreover, they subtend a large visual angle and hence achieve substantial real-world blocking. When used for battle planning, for example, the workbench in fact represents in life size the sandtable devices they displace.

The debate about display format seems to be over. People recognize that each format proves clearly superior for some set of real applications, yet none dominates. In our laboratory at the University of North Carolina at Chapel Hill, we use them all—HMDs, surround projec-

Sutherland's 1965 Vision

Display as a *window into a virtual world*
 Improve image generation until the picture *looks real*
 Computer maintains world model in *real time*
 User *directly manipulates* virtual objects
 Manipulated objects *move realistically*
 Immersion in virtual world via *head-mounted display*
 Virtual world also *sounds real, feels real*

tion, panoramic projection, and workbenches. Each has its own peculiar merits and disadvantages.

Head-mounted displays. The most noticeable advances in HMDs have occurred in resolution, although color saturation, brightness, and ergonomics have also improved considerably. In 1994, one had a choice of costly and cumbersome CRT HMDs, which had excellent resolution and color, or economical LCDs, which had coarse resolution and poor saturation. Today economical LCDs have acceptable resolution (640 × 480 tricolor pixels) and good color saturation.

Field of view still poses a major problem with HMDs, with 45-degree full-overlap about the industry median, at prices in the \$5,000 range.

CAVEs and kin. Many major VR installations now use the surround-projection technology first introduced in the University of Illinois-Chicago Circle CAVE. From three to six faces of a rectangular solid are fitted with rear-projection screens, each driven by one of a set of coordinated image-generation systems.

Standard off-the-shelf projector resolution is now up to 1280 × 1024, better than SVGA (super video graphics array) and even XGA (extended graphics array). In a 10-foot cave, this gives an angular resolution of about 4 minutes of arc; human visual acuity is 1 minute of arc for 20/20 vision.

The principal advantages of surround-projection displays are

- a wide, surrounding field of view, and
- the ability to give a shared experience to a small group (of whom one or none are head-tracked).

Table 1. Progress in VR technologies.

1994	1999
Swimming due to lags	Still a major problem for HMDs and caves, not screens
Displays: narrow field of view or poor resolution or high cost	HMD resolution of 460 by 680 real pixels now affordable Projector resolution 1280 by 1024
Limited model complexity	Rendering limited mostly by cost
Poor registration in augmented reality	Augmented reality dynamic registration still hard; 1 ms = 1 mm error
Tethered ranging	Wide-area tracking available; wireless not yet in use
Bad ergonomics	Ergonomics getting there
Tedious model building	Model engineering a major task

The principal disadvantages are

- the cost of multiple image-generation systems,
- space requirements for rear projection,
- brightness limitations due to large screen size, which results in scenes of approximately full-moon brightness and hinders color perception,
- corner and edge effects that intrude on displayed scenes, and
- reduced contrast and color saturation due to light scattering, especially from opposing screens.

This latter problem, which I notice in UNC's surround-projection VR facility and in all I have visited, seems inherent in the geometry itself. However, careful choice of screen material (Carolina Cruz-Neira of Iowa State University has an unpublished study on this) and probably polarizing glasses can ameliorate the problem. The brightness, contrast, and color saturation problems are serious enough that the team at the Fraunhofer Institute at Stuttgart reports that their client automobile stylists and industrial designers have rejected their cave in favor of Fraunhofer's panoramic display installation. The users do insist on a life-sized display.

Panoramic displays. One or more screens are alternatively arranged in a panoramic configuration. This suits groups especially, and multidisciplinary design reviews commonly use this type of display. One person drives the viewpoint.

Workbenches. The workbench configuration lays a rear-projection screen flat and positions the projector so that the workbench's length approximates that of a human body. One, two, or conceivably more tracked viewers each perceive a custom-generated image. Angular resolution typically is about 4 minutes of arc near the center of the display. Since the eye-to-far-screen-border plane limits the apparent height of an object, many workbenches can be tilted to resemble drafting tables.

Rendering engines

Rendering engines have benefited from significant advances in speed and reductions in cost.

Speed. Rendering engines have improved radically in the past five years (almost four of Gordon Moore's 18-month performance-doubling periods). The complexity of the virtual worlds that could be visualized was sharply limited in 1994, when the fastest commercially available engines had actual speeds of about 600 K polygons per second, or about 30 K polygons in a 1/20-second frame. Today each pipe of an 8-pipe, 32-processor SGI Reality Monster can render scenes of up to 180 K polygons in 1/20 second. Moreover, much larger configurations are available.

In one sense, world-model complexity is more dollar-limited than technology-limited today. In practice, world models containing more than 500 K polygons still require algorithmic attacks to achieve real-time rendering.

Cost. Meanwhile, steady progress in mass-market CPUs yields multi-hundred-megahertz clock speeds. The progress of graphics accelerator cards, driven by the game market, has matched this CPU progress. Consequently, VR configurations of quite acceptable performance can now be assembled from mass-market image-generation engines. For many applications, image generation no longer dominates system cost.

Tracking

In 1994, tracking the viewer's head motion was a major problem. Tracker ranges tethered the viewer to an effective radius of about four feet. Tracker accuracy suffered from severe field distortion caused by metal objects and magnetic fields.

Unlike display technology and image-generation technology, tracking technology has not had a substantial non-VR market to pull it along. The most important collateral market has been motion capture for entertainment applications, and that market has not pressed the technology on accuracy. So progress in tracking has not matched that of displays and image generation.

Nevertheless, progress has occurred. The UNC-Chapel Hill outward-looking optical tracker is routinely operated over an 18 × 32-foot range, with accuracy of 1 mm and 0.1 degree at 1,500 updates per second. Commercial off-the-shelf (COTS) trackers give working range radii of 8 to 10 feet. Hybrid-technology trackers seem most promising, combining inertial, optical, ultrasonic, and/or magnetic technologies.

Ergonomics

With wide-range trackers, another problem emerges—the wires to the user. The physical tether, not too much of a bother when the user was electronically tethered anyway, becomes an ergonomic nuisance once the user can walk around in a room-sized area.

In principle, substituting wireless links for wires can solve this problem. For users in surround-projection systems, COTS wireless systems serve, since only tracking and button-push data need to be transmitted.

For users with HMDs, the problem becomes much more serious—two channels of high-definition video must also be transmitted, and COTS wireless systems do not yet have the required portability. HMDs also require body-mounted power for free-ranging viewers to wear them.

System latency

Perceptually, the greatest illusion breaker in 1994 systems was the latency between user motion and its representation to the visual system. Latencies routinely ran 250 to 500 ms. Flight simulator experience had shown latencies of greater than 50 ms to be perceptible. In my opinion, end-to-end system latency is still the most serious technical shortcoming of today's VR systems.

In HMD systems, head rotation is the most demanding motion, with typical angular velocities of 50 degrees per second. Latencies of 150 to 500 ms make the presented scene “swim” for the user, seriously damaging the illusion of presence. In projection systems, whether surround, panoramic, or workbench, the

viewer's head rotation does not change the generated image—only viewpoint translation, and any motions of the interaction device and of virtual objects. Hence, system latencies are not so noticeable in these systems—but they nevertheless damage the illusion of presence. I see latencies of 150 to 250 ms being accepted without outcry.

Many advances in image rendering speed came through graphics processor pipelining, which has hurt system latency. The designers of tracking systems have given insufficient attention to system latency. Moreover, many VR systems have been pieced together using standard networking between the tracker's computer and the image generator, and this contributes noticeably to latency.

The latency problem becomes extremely serious in augmented reality systems in which the virtual world superimposes on the real world. The challenge lies in dynamic registration—the two worlds should stay rigidly locked together both for the illusion of reality and for task performance. Holloway has studied the viewer motions of a cranio-facial surgeon while examining a patient and developing an operating plan. For those viewer motions, Holloway found that a millisecond of latency translated into a maximum registration error of one millimeter in, for example, superimposing CT scan and/or MRI scan data on the patient's visible face, as perceived by the surgeon through an HMD.⁶ Since the application required millimeter accuracy, and today's best systems have achieved latencies of at best 40 to 50 ms, Holloway chose to pursue the cranio-facial application no further.

The most exciting, although not the easiest, augmented reality applications are surgical. One attack uses video camera technology to acquire the real-world image, which is then video-combined with the virtual image. This approach has in principle two advantages over optical combination—the video real-world image can be delayed to match the virtual image, and obscuration of far objects by near ones can be done symmetrically between the images.

Model engineering

Now that we can explore quite large virtual world models in real time, we find that acquiring, cleaning, updating, and versioning even static world models is itself a substantial engineering task. It resembles software engineering in magnitude and in some, but not all, other aspects. My own rule of thumb is that managing a model of n polygons is roughly equivalent to managing a software construct of n source lines.

Model acquisition. VR practitioners acquire models in one of three ways: build them, inherit them as byproducts of computer-aided design efforts, or acquire them directly by sensing existing objects.

In spite of a variety of excellent COTS tools for model building, it is tedious and costly work, especially when accuracy is important. We have found it takes several man-years to make a model of an existing kitchen that aims at quarter-inch accuracy. (We do not actually aim for that resolution where a textured image will serve as

In my opinion, end-to-end system latency is still the most serious technical shortcoming of today's VR systems.

a substitute, such as the spice rack and contents, or stove knobs.)

I have found a breadth-first iterative-refinement strategy best for modeling. First, make a simple representation of each major object, then of each minor object. Then do a level of refinement on each, *guided by the eye*—What approximation hurts worst as one experiences the world?

Textures are extremely powerful, as SGI's Performer Town first demonstrated. Image textures on block models yield a pretty good model rather quickly. Moving through even a rough model wonderfully boosts the modeler's morale and enthusiasm, as well as guiding refinement.

Buying models. Several firms offer catalogs of models, at different levels of detail, of common objects including people. It is cheaper, and faster, to buy than to build these components of a custom world model.

Inheriting CAD models. By far the simplest way to get superbly detailed models of designed objects, whether existing or planned, is to get the computer-assisted design (CAD) data. But even that rarely proves simple:

- We have found it very difficult to get the original computational-solid-geometry data, which best encapsulates the designer's thoughts about form, function, and expected method of construction. We usually receive an already tessellated polygonal representation. Quite often, it will be severely over-tessellated, needing polygonal simplification to produce alternative models at different levels of detail.
- Formats will almost always have to be translated. Do it in an information-preserving way.
- CAD models often require substantial amounts of manual cleaning. In some CAD systems, deleted, moved, or inactive objects stay in the database as polygonal ghosts. Coincident (twinkling) polygons and cracks are common.
- AutoCAD does not capture the orientation of polygons. Orienting them takes automatic and manual work.
- If any of the subsequent processing programs requires manifolds, making them from CAD data will take much work.
- CAD models, particularly of architectural structures, typically show the object as designed, rather than as built.

Models from images. For existing objects only, as opposed to imagined or designed objects, imaging can

yield models. Imaging may be done by visible light, laser ranging, CAT and MRI scans, ultrasound, and so forth. Sometimes one must combine different imaging modalities and then register them to yield both 3D geometry and visual attributes such as color and surface textures. Recovering models from images is a whole separate technology and an active research area, which I cannot treat here.

Applications

The most important thing in VR since 1994 is not the advances in technologies, but the increasing adoption of its technologies and techniques to increase productivity, improve team communication, and reduce costs. VR is now really real.

Finding the production-stage applications

For my assessment, I broadcast e-mail messages to the mailing list for the Virtual Reality 99 Conference and to the United Kingdom VR Special Interest Group (ukvr-sig), inviting people to send reports of VR applications. I defined three stages of application maturity:

- Demonstration
- Pilot production—has real users but remains in the developers' hands, under test
- Production—has real users doing real work, with the system in the users' hands

I especially invited reports of applications in the pilot and production stages.

In the discussion here, I report on some production-stage applications, that is, employed in dead earnest by users—not developers—for the results gained, rather than as an experiment or trial. This report does not aim to describe all such applications. On the other hand, most published reports do not sharply distinguish the stages of progress of systems. This report describes applications that I know to be in production. In most cases I visited the application site, verified the application's status, and tried to learn what unexpected experiences and lessons have resulted from the process of making them work. In a sense, this spells out "what's real" about some VR applications.

The most surprising result of my call for information on VR projects is how few I could find in mid-1998 that were really in routine production use. Some, of course, are not discussed openly for competitive or security reasons. A great many more were in pilot status, well past the demo stage and almost to the production stage. I believe this situation to be changing very rapidly and that another five years will find VR applications such as those I describe to be much more widespread.

For example, the use of immersive VR for visualization of seismological data has been intensively pursued both in oil companies and in universities. One company, Landmark, is even making major VR installations in the US and in Europe for that purpose. Yet, as far as I could learn by inquiries, no one was quite yet using VR in routine seismic interpretation.

Here are the kinds of verifiable production applications I found:

- Vehicle simulation—first and still much the best
- Entertainment—virtual sets, virtual rides
- Vehicle design—ergonomics, styling, engineering
- Architectural design and spatial arrangement; submarines, deep-sea oil platforms, process plants
- Training—only the National Aeronautics and Space Administration
- Medicine—psychiatric treatment
- Probe microscopy

Of these, vehicle simulation was the first application of what today we call VR. It is not only the oldest, it is also the most advanced. The results accomplished in vehicle simulation provide both an existence theorem and a challenge for other applications: It is possible to do VR exceptionally well, and it pays. Surprisingly, there has been relatively little knowledge interchange between the vehicle simulator discipline and the new VR discipline, due I think to ignorance and sloth on the part of the VR community.

A second batch of for-profit production applications of VR lie in the entertainment sphere. By and large, the most elaborate use of computer graphics in entertainment has been non-real-time graphics, used for animation and special effects, rather than VR. However, theme parks and arcades are increasingly installing true VR experiences. I shall not treat these applications at all here.

Flying a 747 simulator at British Airways

To my delight, I got to spend an hour flying a 747 simulator at British Airways' facility at Heathrow. It was a stunningly good illusion—the best VR I have ever experienced. Rediffusion Ltd. built the simulator, which cost about \$13 million.

The visuals appear on a spherical zonal screen about 12 feet from the pilot and copilot seats. The physical setup faithfully models the interior of the cockpit, and the instruments faithfully display the results of real avionics—the steering yoke seems to fight back properly. The whole pilots' cabin, plus room for the instructor, is mounted on a motion platform that gyrates within a three-story space. The vehicle dynamics and simulated motions appear to be of very high quality. The sound is superb: engine sound, wind sound, taxiing bumps in the pavement, radios.

Within a very few minutes I was not in a simulator, I was flying the airplane: taxiing, taking off, climbing out, circling the airport, and trying to keep the plane at constant altitude. (The 747's dynamics differ markedly from those of the light planes in which I learned to fly years ago.) So compelling was the illusion that the breaks in presence came as visceral, not intellectual, shocks. One occurred when the instructor abruptly changed the scene, from circling above London to an approach to Hong Kong. The other occurred when I taxied up to a hangar in Beijing and looked back (to about 4 o'clock) to ensure that I would not brush wingtips with a parked aircraft—and the view was just empty gray! The projected visuals did not reach that far around.

Lessons. My host, Michael Burtenshaw, explained that their successes drove the steady evolution and uni-

versal adoption of flight simulators to train pilots on new aircraft types. At Heathrow, British Airways now has 18 simulators in four buildings, each specialized to an aircraft type. These they keep busy training both their own pilots and pilots of smaller airlines, to whom they sell instruction. Simulators, though costly, are much cheaper than airplanes. Much more important, pilots can train and exercise in extreme situations and emergency procedures where real practice would imperil aircraft and lives. Many major airlines have similar sets of simulators; so do various air forces.

Increasingly, real avionics, which make up a good chunk of the cost of high-end simulators, are being replaced by individual PCs. Each PC simulates one instrument's behavior and drives its output dials. Significant economies result.

British Airways needs to keep a simulator type as long as it keeps the corresponding aircraft type—up to 25 years. I found it memorable to walk through the facility and see old computers running whose existence I had almost forgotten and whose maintenance is a nightmare for the airline: Xerox Sigma 3, DEC PDP-11, and Vax 11-780.

Merchant ship simulation at Warsash

The Warsash Maritime Centre of Southampton Institute trains both deck and engineering officers for the merchant marine. It offers a two-year cadet course at the technical-school level. A principal undertaking, however, is a set of one-week short courses designed for both the qualification testing and skill enhancement of deck and engineering officers. Shipping companies regularly send deck or engineering teams of four officers to train together, to build team skills. The facility operates routinely as a revenue-producing element of Southampton Institute. David Gatfield served as my host.

Warsash runs a rich set of simulators: an engine-room control system, a liquid-gas cargo-handling simulator, a first-class single-bridge simulator, and a coupled simulator consisting of three bridge simulators, each capable of handling a full deck-officer team, for multiship maneuvers. The best bridge simulator represents a generic merchant vessel, although the view of the ship from the bridge can be customized (via texture mapping) to represent a particular ship type or even a particular vessel. Similarly, the look and feel of the controls can be customized to a small degree, to simulate different bridge configurations (see Figure 1).

The visual surround, approximately 180 degrees, is generated by seven behind-screen Barco projectors. The imagery is generated with 768×576 -pixel resolution by a set of PCs with accelerator cards. Woofers mounted under the floor do a quite convincing job of simulating engine noises for several different power-plant



Courtesy Warsash Maritime Centre, Southampton Institute

1 Ship bridge simulator at Warsash Maritime Centre.

types; other speakers provide wind, wave, buoy, and ship-whistle noises.

The ocean simulation provides a variety of sea states; the sea model includes tides and currents. Atmospherics, including a variety of visibility and fog conditions, are effective. An auxiliary monitor provides the function of binoculars—a higher-resolution, restricted field-of-view image—without the aiming naturalness of true binoculars. Radar, Loran, geographic positioning system (GPS), depth (fathometer), over-the-ground speed indicator, and other instruments are faithfully simulated. Norcontrol built the simulator, which cost approximately £2 million in 1995.

I experienced a ferryboat trip from a southern Norwegian port, at twilight. As wind speed and sea state rose, the most surprising effect was the realism of the vessel's pitch and roll, achieved entirely by manipulation of the imagery. My colleagues and I found ourselves rocking to and fro, and side-to-side, to compensate for the ship motion. One recent visitor, a professional in ship simulation, asked the Warsash people if they had much trouble with their hydraulics. He was surprised when told there were none.

A fascinating non-VR team-training simulator at Warsash consists of a small fleet of 1/12 to 1/25 scale-model merchant ships navigated around a 13-acre lake with some 30 ship-handling hazards or stations. Each ship seats two persons, canoe-style. The master's eyes are exactly at the height of the bridge. He gives oral commands to the pilot, who actually handles the controls. The ship scaling results in a seven-fold scaling-up of the natural breezes and winds.

Wish list. First and foremost, our hosts want more-natural binoculars—an important item often mentioned in student debriefings. Today's commercial off-the-shelf technology offers such capability—it just takes money. Second, they want better screen resolution, and third, more screen brightness. Indeed, the simulator worked well for twilight and night scenes, but could not begin to

2 View of virtual windshield wiper visibility at Daimler-Chrysler's Technology Center.



Courtesy of Daimler-Chrysler

approximate either the brightness or the dynamic range of a sunlight-illuminated scene.

Lessons. As with flight simulators, our hosts report several advantages of simulation over real-ship training:

- Emergency scenarios, even extreme ones, can be thoroughly exercised.
- Scenarios can readily be run, accelerated, and switched, enabling more significant experience time per hour of training.
- Cost.

A few engineering officer teams report that Warsash's large control-board simulator seems dated—their own engine rooms now have glass-cockpit-type controls, everything displayed and actuated via computer screens. Warsash is currently updating the engine-room simulator to reflect this type of control system. I wonder at the human factors effects of seeing everything at once via a visual scan versus having to act to bring up information. Older may be better.

I am convinced that much of the sense of presence and participation in vehicle simulators comes from the fact that one can reach out and touch on the simulator everything reachable on the real vehicle—the near-field haptics are exactly right.

The second take-home lesson for me from experiencing these working simulators is the extreme importance of getting sound right.

Ergonomics and design at Daimler-Chrysler

For years, VR researchers have worked toward making VR an effective tool for product design and design review. Today the automobile industry seems way ahead in adopting the technology for design applications—most major automobile manufacturers have installations or use nearby ones. Some are in routine production status.

I visited one such production system, Daimler-

Chrysler's installation in the Small Car Platform Advance Vehicle Engineering area of their Auburn Hills, Michigan, Technical Center. Ken Socks, Don Misson, and Josh Davidson served as my hosts. The configuration includes a high-resolution stereoscopic Boom by FakeSpace Systems, worn on the user's head as a head-mounted display. The Boom mechanism provides high-accuracy, extremely low-latency mechanical tracking of the user's head pose. The user sits in a "buck"—a real car seat, complete with all its adjustments, combined with a real steering wheel and a mocked-up instrument control panel.

Imagery comes from an SGI Onyx Infinite Reality system. It drives not only the Boom but also a monocular projector that displays on a 4-foot by

6-foot screen at one end of a nearby conference table that seats eight. An Ascension magnetic tracker tracks the positions of the driver's hands (but not the fingers) and of auxiliary objects such as a coffee cup. A short calibration sequence establishes the length and position of the extended index finger relative to the hand tracker. Modal buttons enable the driver to cycle among the conformations of the hand avatars—reaching, holding an object, grasping the steering wheel, and so on.

This installation sees routine weekly use for production design work. I talked with user engineers from groups doing ergonomic studies (driver controls, access from front passenger seat, view, and so forth), windshield wiper design (visibility as a function of body size; see Figure 2), interior trim design (color studies, among others), and painting studies (detecting accidental appearances of exterior paint in the interior, due to metal wrapping). The windshield wiper engineers, for example, report that the system obviates many arguments—a whole team sees together the visibility as perceived by drivers of different body sizes and shapes.

Lessons. A major factor in the success of the Daimler-Chrysler installation: it was desired, funded, specified, and is operated by a user group who really wanted it, the Ergonomics activity within Small Car Platform Advance Vehicle Engineering. They enlisted the (essential) help of the Technical Computer Center in realizing their system. It offers a prime example of user-pull versus technology-push. Consequently, system fixes and enhancements follow the users' priority order, and the corporate know-how for using the system most effectively develops within one of the user groups. Interestingly, use now extends to many departments other than Ergonomics, and the system is used as much for other aspects of design as for ergonomics.

Models provide a second important lesson from the Daimler-Chrysler experience. Some years ago, their laboratories operated a variety of CAD systems. The Engineering Vice President ordered that all CAD would move

to one system; they selected Catia from Dassault Systemes. Since Catia is the design medium, the Catia models of automobiles under design are current, accurate, and maintained—the metal is cut from those models. This means that one of the hardest problems in VR—how to get accurate, detailed models—does not arise for the Daimler-Chrysler applications. The models are byproducts of the design process, and they are furnished by someone other than the VR systems team.

Design review at Electric Boat

VR today remains an expensive technology, more because of the people, the models, and the software than because of the image generation, tracking, and display equipment. Therefore, adoption of the technology for design tasks happened first in applications where the value of design is greatest: mass-produced vehicles and exceedingly complex structures such as submarines and process plants.

The Electric Boat Division of General Dynamics Corporation, which designs and builds nuclear submarines, uses VR principally for multidisciplinary design review. The configuration consists of a large conference room with a panoramic monocular projection system. A single user specifies travel using a mouse, and an SGI Onyx Infinite Reality Engine generates imagery. Electric Boat makes heavy use of four such high-security VR rooms at its Groton, Connecticut, development laboratories. My hosts there were Don Slawski and Jim Boudreaux.

Submarine design is done in and controlled with Catia. Approximately two-thirds of the total design effort (for the vessel, not including its nuclear power plant) goes into the design of piping, wiring, and ductwork. The visualizable model of a submarine contains millions of polygons. This model is derived from the Catia model, transmitted to the visualization file system by “sneakernet,” and displayed using Deneb’s visualization software.

A typical design review session includes not only the various engineering groups involved in a particular design area, but also manufacturing, capital tooling, maintenance, and operations people. During a session the group will usually move to a particular local area and spend many minutes studying it. Viewpoint changes may happen every few minutes to aid study, but not continually. Representatives of each discipline evaluate the proposed design from their own particular points of view, discuss problems, and propose fixes. After the meeting, the responsible engineer details the fixes and enters the changes into the Catia system manually, through the normal change-control process. The normal structural, stress, acoustic, and other analyses are run, usually as batch operations, on the changed design.

In particular, the oft-imagined scenario in which the visiting admiral says “Move that bulkhead one foot aft!” and the change is immediately effected in the master model is not how things are done, of course. Such a thing would be technically very difficult for the VR system, to be sure. But such a scenario would not happen even with magical technology, because design discipline demands the human and computational analysis of all the interactions and effects of any proposed change.

Experienced engineering organizations have quite formal change-control processes.

The design and design review processes as described by my hosts at Electric Boat corresponded closely to those described to me at Newport News Shipbuilding in Newport News, Virginia, who make aircraft carriers and other ships, and at Brown and Root Engineering Division of Halliburton in Leatherhead, Surrey, UK, who design off-shore oil platforms.

Lessons. All the engineering organizations perceive large advantages from VR walkthroughs as a part of design reviews.

In one review at Electric Boat, a capital tooling person from the factory pointed out that a certain massive semicylindrical tank could be better fabricated as a cylinder—for which they had extant tooling—then cut in half and roofed, saving thousands over the engineer’s proposed fabrication from piece parts.

In a multidisciplinary design review at Brown and Root, the painters from the maintenance force remarked that certain fixtures on an oil platform should be made out of extra-heavy-gauge steel because “We can paint its interior once in the shop, but we’ll never again be able to paint it after you’ve installed it like that.” The designers chose to change the configuration.

In describing their two years of experience, my hosts at Brown and Root—Arthur Barker and Martin Williams—said that the most important effects of their installing and using their VR theater and its associated telecommunications was not effects on designs, but effects on the design processes, in particular the communication of ideas between the Halliburton divisions in London and in Houston. Indeed, they now plan to design a South American project in Brazil and to design-review it from Leatherhead.

These groups find true scale for structures is important for detailed understanding. This is, I believe, the major advantage that HMDs, caves, and panoramic displays have over so-called desktop VR. I think the advantage justifies the extra cost when dealing with complex structures.

Second, system latency—a major concern in the VR laboratory—is not necessarily a showstopper for this application, because viewpoint motion is slow and infrequent, due to the intense study going on.

Design review at John Deere

The experience of the Construction Machinery Division of John Deere as it has moved toward virtual prototyping proves instructive. Pilot studies of VR at the Moline, Illinois division began in 1994, but nothing much really happened until a key technical person joined in 1996. The configuration is rather typical: an SGI Onyx Infinite Reality, a head-mounted display, an Ascension Flock of Birds tracking system, Division’s dVise software, and the Jack human model for ergonomic studies. Zones of reach and zones of comfort, provided by Engineering Animation Inc.’s Pro-Engineering software, are shown superimposed on the virtual models.

Jerry Duncan and Mac Klinger served as my infor-

3 NASA-Houston's "Charlotte" Virtual Weightless Mass lets astronauts practice handling weightless massy objects.



Courtesy of NASA

ments. Four wins to date reflect the sort of savings resulting from the nontrivial investment in VR. The first study was a styling study for a new machine, normally done with a sequence of fiberboard mockups. The VR model displaced two-thirds, but not all, of the usual mockups and saved \$80K in mockup cost—real savings only if you already have a CAD model of the prototyped object.

The second win was a safety technology evaluation formerly done on an iron prototype, successfully performed in VR. This evaluation studies, among other things, encumbrances and egress in emergencies. A six-person jury performs the evaluation, using a formal protocol. It normally takes two days, because each jury member climbs into the prototype, evaluates the next group of items on the checklist, and climbs back out. The VR evaluation had the whole jury viewing the video projection on a screen while one person, wearing the head-mounted display, did the various maneuvers. Obviating the serialized access to the cab shortened the whole process to three hours. The whole jury saw and discussed each aspect from a common eyepoint, focusing the discussion. The savings were both man-hours and the construction of the iron prototype.

The third win was exactly the kind hoped for with virtual prototype design review. The issue was steps and handholds, for all kinds of body sizes—a matter that seems minor but makes big differences in usability. Three entire rounds of review and change were effected in five days—with *no iron-cutting*.

Finally, Deere was able to conduct early customer tests of the new 450-H Crawler-dozer using the virtual prototype, well before they could have done them with an iron prototype.

Wish list. The most strongly desired tools are geometry manipulation tools, ways of easily specifying interactions with the design. This includes collision detection and collision response. The great desire is for interfaces simple enough for the occasional user to participate in model changing. Then, since they too find that CAD tools

over-tessellate curved parts, they wish for a suite of tools for polyhedral simplification and for file management for large models and many versions of models.

Lessons. The foresight and activity of an advocate at the corporate technical level facilitated experimentation and then adoption of VR technology at the division level. The vision at the corporate level for John Deere as a whole encompasses not only VR for rapid virtual prototyping of products, but for analysis and evaluation as well as design. And the vision encompasses not only products, but also manufacturing processes, for more Deere people are engaged in the manufacturing process than in product design.

An important insight is that the farther downstream a design gets from its conceiver, the better the visuals must be to convey an accurate, *internalized* perception of the design to those who must build, maintain, and use it. The creating engineer can visualize from a sketch, and the experienced toolmaker from an engineering drawing, but a factory-floor foreman or an operations person may be unable to visualize from anything short of a detailed, realistic picture.

As all the examples above indicate, each user of VR for design has found that it radically facilitates communication among the design team. This may be the most dramatic and cost-effective result.

John Deere has for some time collaborated with the VR research group at Iowa State University, where Carolina Cruz-Neira showed me around. The company sees the Iowa State work as a technical forerunner and ground-breaker for Deere's own in-house applications. The Iowa State group, for example, has a Deere tractor buck mounted in a cave configuration, with a detailed model of a particular Iowa farm, acquired by GPS surveys. John Deere currently operates a more modest configuration for its production work, with exploratory work done at the Iowa State facility. I saw this pattern emerging in several places, including automobile companies that use the Fraunhofer Institutes in Stuttgart and Darmstadt as the sites of their explorations. It makes a lot of sense to me. University research groups should be in the trailblazing business, and the degree to which others then follow those trails indicates the excellence and relevance of the research.

Astronaut training at NASA

Training applications in routine production status proved hard to find, although quite a few are far along in prototype status. The training work with the longest experience—several years as a production operation—seems to be that of NASA-Houston for training astronauts for extra-vehicular activity, where Bowen Loftin and David Homan served as my hosts.

It's hardly surprising that NASA's astronaut training should lead the way; the training has very high value,



4 Vietnam war simulation at the Atlanta Veterans Administration Hospital (a) in use. (b) Imagery seen by the user.

and the alternatives to VR technology are few and poor. Of course, much training can be used vehicle mockups. Weightless experience can be gained in swimming pools and 30-second-long weightless arcs in airplanes. Nonetheless, extra-vehicular activity is very difficult to simulate.

A difficult skill, for which VR training has proven very powerful, is flying about in space using the back-mounted flight unit. It is like no earthly experience. Newton's laws apply ideally—with no drag, an object in motion or rotation continues forever unless stopped. The flight unit is designed principally as an emergency device for use if an astronaut's tether breaks; velocities are very slow. The NASA VR configuration for this is rather standard: an SGI Onyx Infinite Reality for imagery generation, head-mounted displays, and magnetic tracking. An astronaut said the resulting system was the most faithful flight simulator he had used.

Moving around on the outside of a space vehicle is another unearthly skill. The VR system lets astronauts practice the careful planting of hands and feet in rock-climbing fashion. Difficult and unprecedented team tasks, such as correcting the Hubble telescope mirror's optics, made new training demands. The additional unearthly experience for such tasks is the team-coordinated moving of massy but weightless objects. The dynamics are, of course, totally unfamiliar, and viscous damping seriously confounds underwater simulation. For this training, NASA augments visual simulation with a unique haptic simulator called "Charlotte" after the spider of the same name. A real but very light 2-foot cubical box attaches to motors on the corners of an 8-foot cubical frame, as shown in Figure 3. As pairs of astronauts move the object by its handles, the system simulates the dynamics and drives the motors appropriately. Users report very high fidelity for masses of 300 pounds and up.

Lessons. Interaction with objects in virtual worlds still challenges VR researchers. So much of our interaction with objects depends on how they *feel*—purely visual simulation misses realism much too far. This is critical for some training tasks; we really do not know how important it is for design tasks.

Early adoption of VR, even with less-than-satisfactory technologies, enabled NASA to get the years of experience that brought their applications to their present effectiveness.

Collaboration with researchers at the University of Houston has worked much like the John Deere-Iowa State collaboration. The university can do wider exploration and trailblazing; the mission agency does the focused work that leads to production applications.

Psychiatric treatment at Georgia Tech-Emory

Research collaborators at Georgia Institute of Technology and the Emory University Medical School have explored the use of VR for psychiatric treatment. Larry Hodges, Barbara Rothbaum, and David Ready hosted my visit there.

The success of this research has led to the development and fielding of a COTS system by Virtually Better, Inc. They offer a system for about \$18K, approximately \$8K for the hardware and \$10K for software for one application. Eight installations are already in production around the US and one in Argentina, all routinely used by practicing psychiatrists and psychologists. These practitioners do not have computer support locally; any necessary support comes by telephone from Atlanta.

The hardware configuration consists of a PC, a graphics accelerator card, a Virtual Research V-6 or V-8 head-mounted display, and a magnetically tracked bat. A good deal of attention has gone to audio quality; the visuals look rather cartoonish.

The most popular and cost-effective application treats fear-of-flying. The conventional treatment has the practitioner and patient together make multiple trips to an airport, sit on an airplane mockup, sit on an airplane, fly a short hop, and so on. Much expensive practitioner time disappears in travel. The effectiveness of the VR treatment seems just as good as the conventional one, although there are no formal studies yet. The cost is radically lower. Virtually Better also offers fear-of-heights and fear-of-public speaking simulation packages.

The most dramatic procedure offered, in routine use at the Atlanta Veterans Administration Hospital, treats post-traumatic stress disorder for Vietnam War veterans. Physiological monitoring of the patient augments

5 View of UNC nanoManipulator connected to an atomic force microscope.



Courtesy of Russell Taylor

the VR configuration, to give an independent measure of his emotional stress level. The psychologist gently leads the patient into a simulated Vietnam battle scene (see Figure 4), step-by-step recreating the situation where the patient “locks up” in reliving his stress experience. By leading the patient completely through the scene and out the other side, the psychologist aims to help the patient learn how to get himself out of the damaging patterns.

So far, the treatment seems to help the patients who persevere. About half of the first 13 opted out, perhaps because of the realism of the recreated experiences. Studying tapes of typical sessions, I was struck by how completely the patients are present and involved in the simulated Vietnam situation. It hurts to watch them relive painful experiences.

A second installation of this application is under way at the VA hospital in Boston.

Lessons. The big lesson for me was the power of aural VR for reproducing an overall environment. Larry Hodges, the computer scientist on the team, thinks that audio quality is, in several of their applications and experiments, consistently more important than visual quality. His Vietnam simulation certainly supports that opinion.

Indeed, the Fraunhofer IAO (Industrial Engineering Institute) at Stuttgart has a prototype VR application, the routine quality testing of electric drills after manufacture, in which the only VR environment is aural. A sound shower displays the sound field of a well-made drill all over the test cell, facilitating aural comparison. It uses no visuals at all.

I am also impressed with the importance of full-scale immersion for the Vietnam application. It is hard to believe that desktop VR would even begin to achieve the same effects.

nanoManipulator at UNC-Chapel Hill

Probe microscopes, including atomic force microscopes, scanning tunneling microscopes, and near-field

optical microscopes, form images by scanning a probe across the surface of a sample, yielding one or more scalar functions of the two dimensions. Resolution to the nanometer can be obtained; even individual atoms can be imaged under best conditions. As significantly, the tip of the probe can modify the sample, by mechanical or electrical action.

Researchers at the University of North Carolina at Chapel Hill applied VR technology to the task of making the using scientist think and act as if shrunk by a factor of 10^5 to 10^6 and present on the surface, in a VR system called the nanoManipulator. (An alternative way of thinking about it is that we expand the sample by such a factor, to laptop sizes.) The scientist controls the viewpoint and the lighting on the dynamically updated image of the sample, as the microscope continues to scan. He may, if he chooses, suspend scanning, position the probe to a particular spot, and make measurements there. Alternatively, he may take control of the probe and effect the modifications as if he were scratching the surface directly. Russell Taylor and Richard Superfine are leading this project.

Perception is effected two ways: through a stereo visual image rendered on an SGI Onyx Infinite Reality engine and displayed to a head-tracked observer on a workbench or a desktop monitor, and through a Sensable Systems Phantom haptic display (see Figure 5). The user holds this motor-controlled stylus like a pen; sensors yield 4D measurements of position and pose of the tip. Motors provide three to six degrees of force output. The nanoManipulator currently presents three degrees of force output. Moving the Phantom manually controls tip position and action.

The haptic display and control prove essential for manipulations. Since the probe can either image or scrape, but not both at the same time, the scientist is blind while manipulating the surface with the microscope probe. The standard technique has the scientist image the sample, manipulate the probe while working blind but seeing the previous image, then image again to find out what really happened. Although the probe cannot produce images while being used for manipulations, it does produce the control signals that display as vertical or lateral forces. So the scientist can *feel* what he’s doing even when he cannot *see* what’s going on.

The sensation of interacting with a real macroscopic sample on a workbench is very strong. For this application, the size and small field of view of a desktop monitor does not hinder perception because the virtual object is created “full size,” as if on a workbench

Replications of the nanoManipulator system have been installed in four locations in the US and Europe. In routine daily use, they produce science published by physicists, chemists, gene therapists, and others.⁷

Lessons. This application illustrates and emphasizes the fruitfulness of haptics in a VR configuration. It offers an almost ideal application of the Phantom, which can display only the forces on a point probe. Since the microscope can only measure forces on a point probe, the two match well.

Therefore, the methods of interaction seem quite natural for both probe motions and for head, sample, and light motions to improve viewing. Early research work showed that realistic haptic rendering requires update rates greater than 500 updates per second. The Phantom runs at 1,000 updates per second, which seems quite satisfactory.

Second, each VR display mode has some application for which it provides the optimal solution. This one is a natural for a projection-display workbench, a workbench equipped with a haptic display.

Hot open challenges

Although VR has crossed the high pass from “almost works” to “barely works,” many challenges remain both in the enabling technologies and in the systems engineering and human factors disciplines. The tasks that seem most crucial to me follow:

Technological:

- Getting latency down to acceptable levels.
- Rendering massive models (> 1 M polygons) in real time.
- Choosing which display best fits each application: HMD, cave, bench, or panorama.
- Producing satisfactory haptic augmentation for VR illusions.

Systems:

- Interacting most effectively with virtual worlds:
 - Manipulation
 - Specifying travel
 - Wayfinding
- Making model worlds efficiently:
 - Modeling the existing world—image-based techniques look promising
 - Modeling nonexistent worlds—through CAD byproducts or hard work
- Measuring the illusion of presence and its operational effectiveness

How the field addresses these challenges will dramatically affect the continuing success and speed of adoption of VR. I look forward to seeing substantially more projects move from prototype to production status in the near future. ■

Acknowledgments

A major part of this report was given as a keynote address at the Virtual Reality 99 conference.

My greatest thanks go to the correspondents who sent me descriptions of their VR projects, and most especially to those who welcomed me to their installations and shared with me their experiences and the lessons they drew from them. The project descriptions list the principal hosts at each installation; each had colleagues who also shared their knowledge and time. I am most grateful to each of them.

An imaginative grant from the Office of Naval Research, arranged by Larry Rosenblum, made possible the travel by which I gathered the solid first-hand knowledge of applications that are really in production

status. I also thank my faculty, staff, and student colleagues at Chapel Hill, who have taught me many lessons about virtual reality and who continually amaze me with their creativity and accomplishment. Henry Fuchs, in particular, has shared the vision and inspired my efforts by his own immense imagination.

References

1. I.E. Sutherland, “The Ultimate Display,” invited lecture, IFIP Congress 65. An abstract appears in *Information Processing 1965: Proc. IFIP Congress 65*, Vol. 2, W.A. Kalenich, ed., Spartan Books, Washington, D.C., and Macmillan, New York, pp. 506-508. A similar, but quite complete, paper is Sutherland’s “Computer Displays,” *Scientific American*, Vol. 222, No. 6, June, 1970, pp. 57-81.
2. F.P. Brooks, “Is There Any Real Virtue in Virtual Reality?,” public lecture cosponsored by the Royal Academy of Engineering and the British Computer Society, London, 30 Nov. 1994; <http://www.cs.unc.edu/~brooks>.
3. S. Coleridge, *Biographia Literaria*, Ch. 1, in *The Collected Works of Samuel Taylor Coleridge*, Vol. 7, J. Engell and W.J. Bate, eds., Routledge & Kegan Paul, London, and Princeton University Press, Princeton, 1983.
4. N.I. Durlach and A.S. Mavor, eds., *Virtual Reality—Scientific and Technological Challenges*, National Research Council, Washington, D.C., 1995.
5. G. Burdea and P. Coiffet, *Virtual Reality Technology*, John Wiley, New York, 1994.
6. R.L. Holloway, *Registration Errors in Augmented Reality Systems*, PhD dissertation, Department of Computer Science, University of North Carolina at Chapel Hill, 1995.
7. M.R. Falvo et al., “Bending and Buckling of Carbon Nanotubes under Large Strain,” *Nature*, Vol. 389, Oct. 1997, pp. 582-584.



Frederick P. Brooks, Jr. is Kenan Professor of Computer Science at the University of North Carolina at Chapel Hill, where he founded the department in 1964. His current research field is interactive 3D computer graphics. He received his PhD

in 1956 in what would today be called computer science, under Howard Aiken at Harvard. His AB was in physics from Duke.

While Brooks worked for IBM, he was finally project manager for the development of the System/360 family of computers and of its software, Operating System/360, for which he was awarded the National Medal of Technology and the IEEE John von Neumann Medal. His recent books are *The Mythical Man-Month: Essays on Software Engineering (20th Anniversary Edition, Addison-Wesley, Reading, Mass., 1995)* and, with G.A. Blaauw, *Computer Architecture: Concepts and Evolution (Addison-Wesley, 1997)*. He is a fellow of the IEEE and a member of the National Academy of Engineering.

Readers may contact him at brooks@cs.unc.edu.