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THE CAVE™ AUTOMATIC VIRTUAL ENVIRONMENT: CHARACTERISTICS AND APPLICATIONS¹

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INTRODUCTION

Virtual reality may best be defined as the wide-field presentation of computer-generated, multi-sensory information that tracks a user in real time. In addition to the more well-known modes of virtual reality – head-mounted displays and boom-mounted displays – the Electronic Visualization Laboratory at the University of Illinois at Chicago recently introduced a third mode: a room constructed from large screens on which the graphics are projected on to three walls and the floor.

The CAVE is a multi-person, room-sized, high-resolution, 3D video and audio environment. Graphics are rear projected in stereo onto three walls and the floor, and viewed with stereo glasses (Ref. 1). As a viewer wearing a location sensor moves within its display boundaries, the correct perspective and stereo projections of the environment are updated, and the image moves with and surrounds the viewer. The other viewers in the CAVE are like passengers in a bus, along for the ride!

“CAVE,” the name selected for the virtual reality theater, is both a recursive acronym (Cave Automatic Virtual Environment) and a reference to “The Simile of the Cave” found in Plato’s “Republic,” in which the philosopher explores the ideas of perception, reality, and illusion. Plato used the analogy of a person facing the back of a cave alive with shadows that are his/her only basis for ideas of what real objects are.

Rather than having evolved from video games or flight simulation, the CAVE has its motivation rooted in scientific visualization and the SIGGRAPH 92 Showcase effort. The CAVE was designed to be a useful tool for scientific visualization. The Showcase event was an experiment; the Showcase chair, James E. George, and the Showcase committee advocated an environment for computational scientists to interactively present their research at a major professional conference in a one-to-many format on high-end workstations attached to large projection screens. The CAVE was developed as a “virtual reality theater” with scientific content and projection that met the criteria of Showcase.

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¹ This research was supported by NSF Grant number IRI-9213822.

GENERAL CHARACTERISTICS

The CAVE is a theater 10x10x9', made up of three rear-projection screens for walls and a down-projection screen for the floor (Figure 1). Electrohome Marquee 8000 projectors throw full-color workstation fields (1280x492 stereo) at 120 Hz onto the screens, giving between 2,000 and 4,000 linear pixel resolution to the surrounding composite image. Computer-controlled audio provides a sonification capability to multiple speakers. A user's head and hand are tracked with Ascension tethered electromagnetic sensors. Stereographics' LCD stereo shutter glasses are used to separate the alternate fields going to the eyes. A Silicon Graphics Onyx with three Reality Engines is used to create the imagery that is projected onto three of the four walls. The CAVE's theater area sits in a 30x20x13' light-tight room, provided that the projectors' optics are folded by mirrors (Ref. 2).

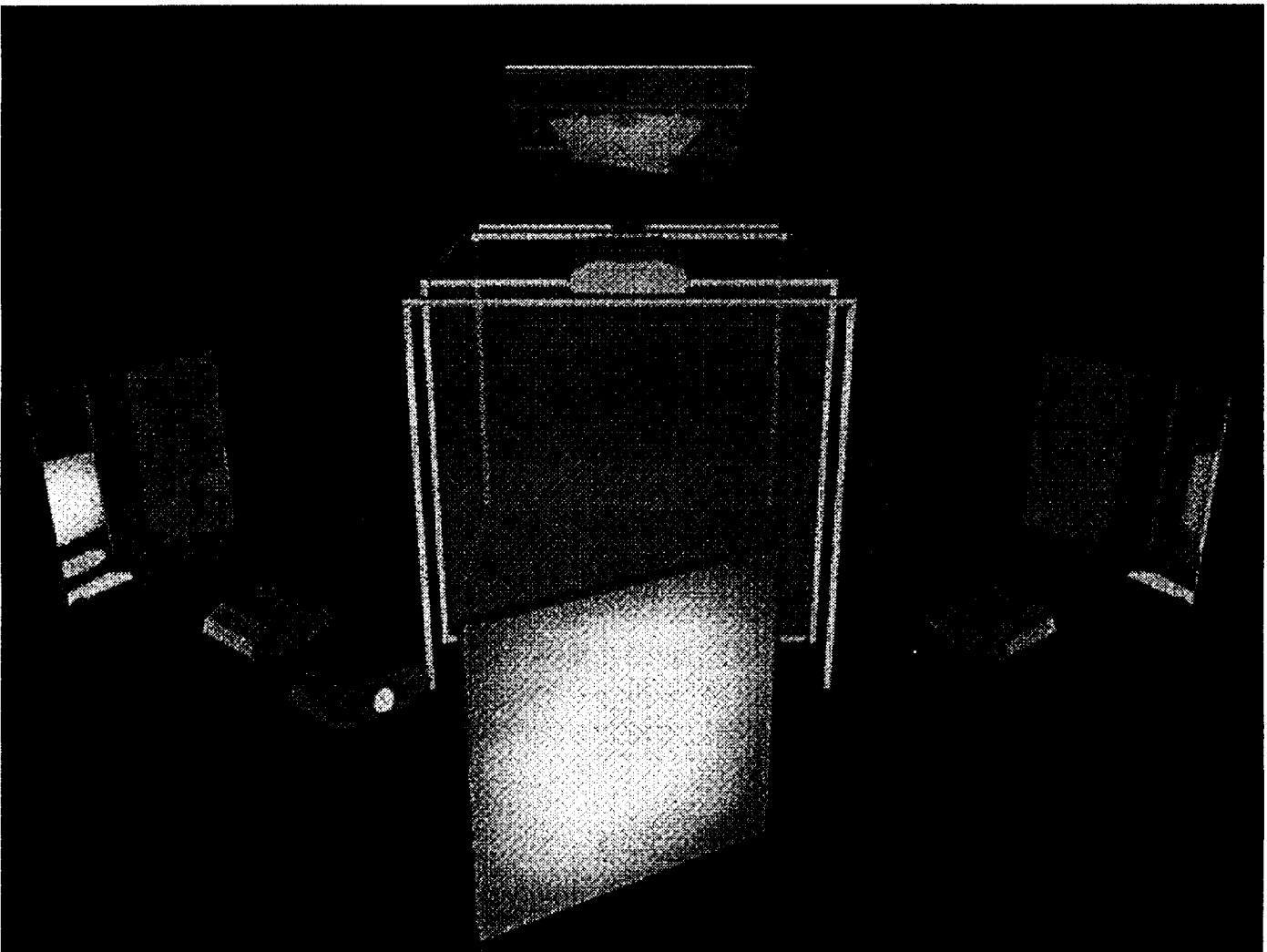


Figure 1. The CAVE

CAVE CHARACTERISTICS

Over the past two years, as we considered building the CAVE, there were several inherent problems with head-mounted virtual-reality technology to which we gave a great deal of thought:

- a. Simplistic real-time walk-around imagery
- b. Unacceptable resolution (the popular head-mounted displays offer resolution that is twice as bad as being legally blind)
- c. Difficulty of sharing experiences between two or more people
- d. Primitive color and lighting models
- e. No capability for successive refinement of images
- f. Too sensitive to rapid head movement
- g. No easy integration with real control devices
- h. Disorientation a common problem
- i. Poor multi-sensory integration, including sound and touch

The CAVE has the current capabilities and engineering characteristics:

- **Multi-person Virtual Environment**
- **Back projection onto 10'x10'x9' room**
- **Wide field-of-view**
- **High resolution color images**
- **Inside-out surround 3-D video presentation**
- **Off axis stereo projection**
- **Head and hand-tracked user interaction**
- **Co-existing real and virtual objects**
- **3-D Audio**
- **SGI Onyx with 3 Reality Engine 2s**
⇒ **2 adjoining walls and the floor**
- **No force or tactile feedback (yet)**
- **Expensive**

Figure 2

VIDEO SYSTEM

The CAVE has an inside-out viewing paradigm where the design is such that the observer is inside looking out as opposed to the outside looking in (Ref. 3). The CAVE uses “window” projection where the projection plane and the center of projection relative to the plane are specified for each eye, thus creating off-axis perspective projection (Ref. 4). The correct perspective and stereo projections are based on cues returned by the Ascension position sensor attached to the Stereographics Crystal Eyes stereo shutter glasses. Each screen updates at 96 Hz or 120 Hz with a resolution of 1025x768 or 1280x492 pixels per screen, respectively. Two off-axis stereo projections are displayed on each wall. To give the illusion of 3-D, the viewer wears stereo shutter glasses that enable a different image to be displayed to each eye by synchronizing the rate of alternating shutter openings to the screen update rate. When generating a stereo image, the screen update rate is effectively cut in half due to the necessity of displaying two images for each 3-D image. Thus, with a 96 Hz screen update rate, the total image has a maximum screen update rate of 48 Hz. The CAVE has a panoramic view that varies from 90° to greater than 180° depending upon the distance of the viewer from the projection screens. The direct viewing field of view is about 100° and is a function of the frame design for the stereo glasses.

However, the reduction in resolution and update rate could be overcome with some design changes to the CAVE's current display system (Figure 3 bullet 1) or to future projector systems (Figure 3 bullet 2). For example, doubling the number of projectors per screen along with the number of graphics processors would restore the display to the original resolution (1024 horizontal lines) and update rate (96 Hz). To restore stereovision without shutter glasses the user would wear passive crossed polarizers with matching polarizers on the corresponding projector.

- **Electrohome high resolution projectors**
 - ⇒ **1024 x 1280 resolution**
 - ⇒ **Quick response time**
 - ⇒ **Fast green phosphor**
- **Future use of LCD lightvalves**
 - ⇒ **GII Wall at SuperComputing 95**
 - ⇒ **Crossed polarizers; not sequential video**
 - ⇒ **Polarizers in CAVE:**
 - **Folded optics problem**
 - **2 projectors per wall**
 - **Alignment**

Figure 3

VISUAL CHARACTERISTICS

Current VE applications are in some ways more ambitious and run on systems that have less computational power than current flight simulation applications. A chief attribute provided by most VE applications that can impact system performance, is user interaction with proximal virtual objects. To work effectively with objects at close range a user requires that the VE provide stereovision. This one necessity alone creates a series of constraints affecting the virtual environment. Stereovision requires that the user's current head position and orientation in the space be used so that the correct perspective views for each eye are generated. Without such information the 3-D world appears distorted. Consequently, the need to know head location forces the use of head tracking equipment that can compromise overall system performance in areas such as image update rate and lag (Ref. 5).

- **1024 x 768 Stereo resolution/screen**
- **2000 x 2000 Linear pixel resolution**
- **90° to 180° Horizontal Field-of-view**
- **100° Vertical Field-of-view**
- **Virtual object float inside CAVE**
⇒ **Users can walk around objects**
- **Low screen brightness**
- **Accommodative stimulus at the screen**
- **Convergence stimulus on object**

Figure 4

AUDIO SYSTEM

At this time only directional sound is produced by the CAVE audio system but future plans call for 3-D audio production using Head-Related Transfer Function (HRTF). A MIDI synthesizer is connected via Internet/PC so, for example, sounds may be generated to alert the user or convey information in the frequency domain. Since the introduction of new systems to make the measurement of individual HRTFs more tractable, 3-D audio will soon be applied to the CAVE. However, at this time, only one person can be tracked and therefore the 3-D sound can only be correct for that person. This is a significant problem for systems that accommodate multiple users of the same environment such as the CAVE (Ref. 6).

- **6 Speaker system with controller**
 - ⇒ **General directional sound**
- **3-D Audio**
 - ⇒ **HRTF computed audio through earphones**
 - ⇒ **Head tracked for one person only**
 - ⇒ **Difficult for multiple users**

Figure 5

MAGNETIC TRACKING SYSTEM

Head and hand position are measured with the Ascension Flock of Birds six degree-of-freedom electromagnetic tracker operating at a 60 Hz sampling frequency for a dual sensor configuration. The normal and the augmented operation of the tracker in the CAVE is outlined in Figure 6. The transmitter is located above the CAVE in the center and has a useful operating range of 6 feet. Head position is used to locate the eyes to perform the correct stereo calculations for the observer. The CAVE's second position sensor is used to allow the viewer to interact with the virtual environment. Since this system is nonlinear and such nonlinearities can significantly compromise the virtual experience of immersion for the user, a calibration of the tracker system is needed. Nonlinearities caused by the metallic objects and electromagnetic fields created by other devices resident in and about the CAVE are compensated to within 1.5% by linearizing values returned by the head tracking system using a correction table containing calibrated positions in the CAVE (Ref. 7).

- **Dual Sensor 6 DOF magnetic tracking system**
- **Normal Range of operation 6 ft. radius**
- **Linear range reduced by distortions**
 - ⇒ **A 3 ft radius**
 - ⇒ **EM devices about the CAVE**
- **Extended linear range with calibration**
 - ⇒ **Nonlinearities reduced**
 - ⇒ **Accuracy improved for position**
 - ⇒ **Rotation calibration in progress**

Figure 6

CAVE CALIBRATION

The goal of the calibration procedure (outlined in Figure 7) is to correct for static position errors in the magnetic tracker. Metal structures near the tracker distort the magnetic field, so the CAVE screen frame is made of austenetic stainless steel which is non-magnetic and has a low conductivity. However, other components needed for the CAVE to function such as projectors and mirrors significantly distort the field. These distortions produce errors in the position component of the 6-degree-of-freedom magnetic tracker. By comparing the output with a custom-built ultrasonic measuring system to the position reported by the magnetic tracker, a look-up table is created from the collected difference data and is used to interpolate for corrected values. The error of the resulting corrected magnetic tracker position is measured to be less than 5% over the calibrated range

- **CAVE filled with array of cubic calibration locations**
- **Magnetic/Sonic Calibration probe**
- **Probe placed inside cube**
- **X,Y,Z location recorded by sonic system**
- **Sonic data correlated to simultaneous Magnetic data**
- **Calibration array generated and data interpolated from lookup table**

Figure 7

CALIBRATION METHOD

The CAVE is first filled by a 3D stereo graphic image of 1-inch boxes on 1-foot intervals (Figure 8). A 1-inch cursor shows the position of the magnetic sensor which is placed atop the ultrasonic measurement device (UMD). A person wearing 3D glasses holds the UMD reasonably straight and moves it until the displayed cursor is inside of each box. The program records the position given by the magnetic sensor and the Onyx sends a signal to the PC to get the position measured by the UMD. This procedure continues until all the boxes in the tracker range inside the CAVE are thus sampled. In practice less than 400 points are collected, essentially all points in the center of the CAVE.

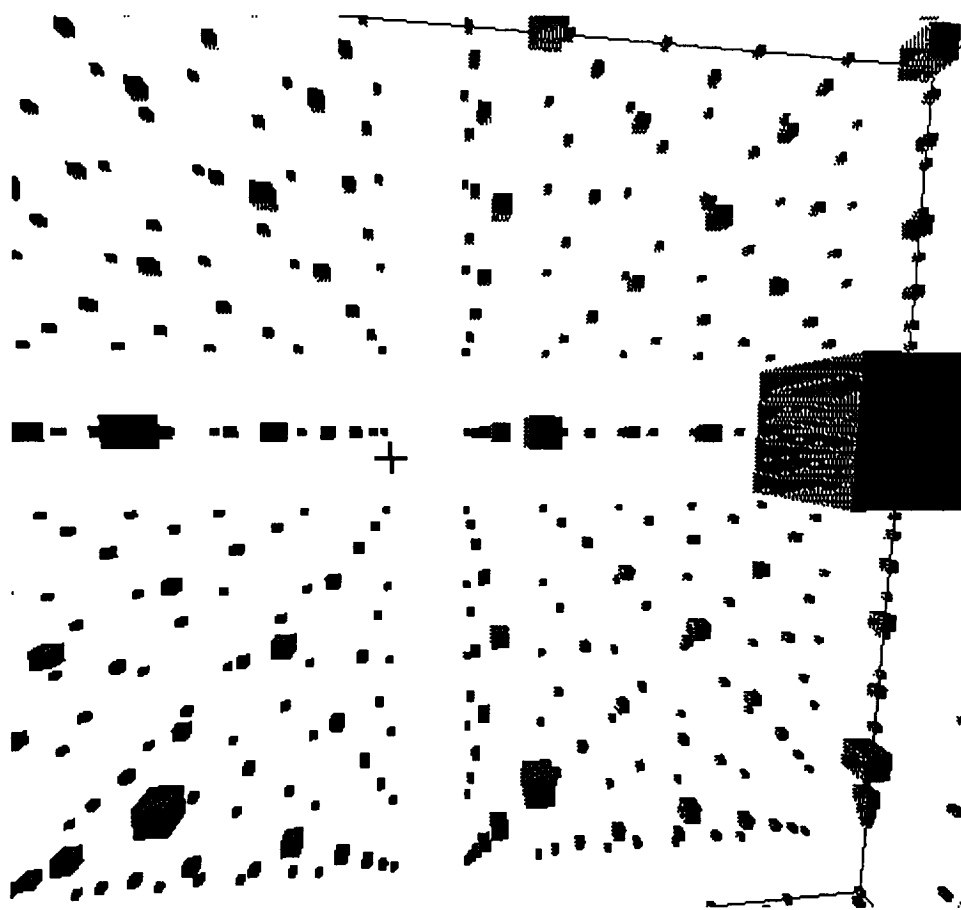


Figure 8

EFFECTS OF CALIBRATION

To measure residual errors after calibration we collected data at one foot intervals on half-foot centers instead of one foot interval on one foot centers. Therefore we measured residual errors half way between the calibration points. These results are shown in the figures below. They show a dramatic reduction in position error after the calibration is performed. These measurements of course depend on the accuracy of the UMD (less than 1.5% over 10 ft.). The maximum error before calibration is seen to be 4 ft. over a 10 ft. range (40%) (Figure 10). The error after calibrating is 0.27 ft. in the same 10 ft. range (2.7%). Similarly, the maximum error before calibration is 0.6 ft. in a 3 ft. range (20%). The error after calibrating is 0.13 ft. over the same range (4.3%). Clearly, this procedure is better at correcting larger errors than smaller ones, why this is true is not well understood at this point. Minimizing tracker latency is desirable in VR systems, so it is important that the correction computation does not substantially increase existing tracker latency. This linear interpolation method needs 30 additions and 72 multiplications for each correction. On the CAVE Onyx R4400 processor, the above calculation takes less than 10 microseconds. Since the theoretical minimum tracker latency is 21 milliseconds, adding 10 microseconds of delay is negligible.

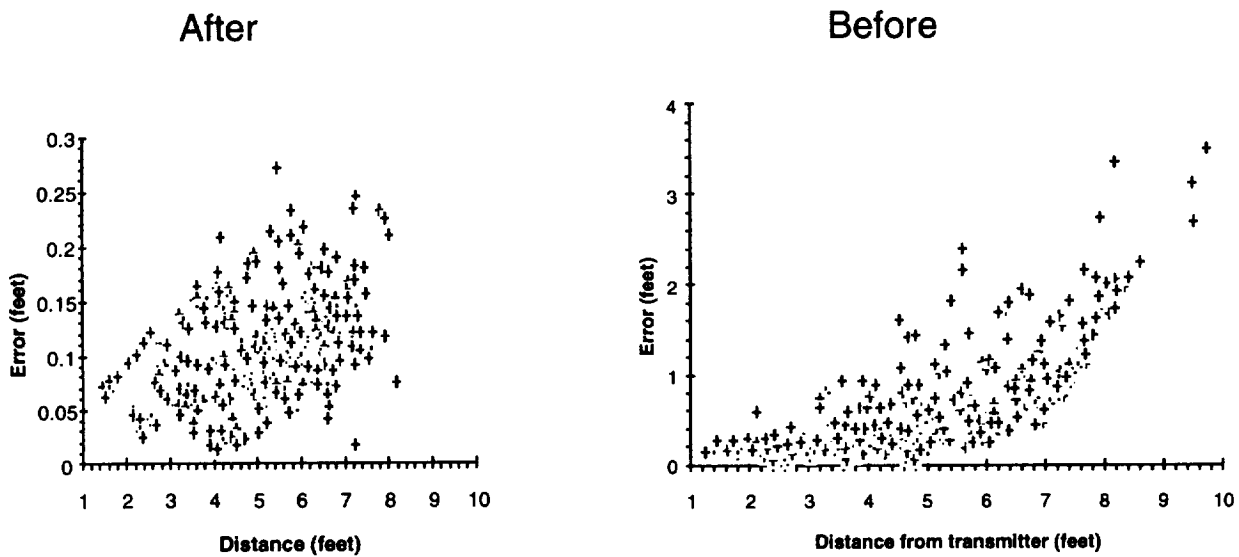


Figure 9

UPDATE RATES

As with most VR systems, the CAVE has a significant delay between the motion of the sensor and the resulting movement of the computer-generated scene. Currently, the minimum delay in the CAVE is in excess of 100 ms. Preliminary figures given of the characteristics in Figure 10 are:

1. Tracker to computer via RS232 line	=> 16 ms (Dual sensor Ascension Tracking System)
2. Serial port to shared memory area	=> 50 ms (Assuming no dedicated Onyx processor)
3. Shared memory area to rendering process	=> 20 ms (CAVE Library delay)
4. Rendering of the scene (variable)	=> 21 ms (Minimum for stereo)
TOTAL	107 ms

- **Stereo Image Update: 96 Hz**
- **Dual Sensor Magnetic Tracker: 60 Hz**
- **UNIX serial line handler: Bottleneck**

Figure 10

SYSTEM LAG

Some of the sources of system lag are outlined in Figure 11. We hope to reduce tracker delay to below 50 ms with improved serial interface cards that use IEEE 488 rather than RS232 protocol. The second largest item of 50 ms delay (in Figure 10) will decrease when a single processor is completely dedicated to the task of acquiring data from the serial port for use by the CAVE library routines. Without a dedicated processor, the delay for this process jumps to 80 ms. The reasons for this large delay are not clear at this time and software improvements will be needed to make this a more reasonable value. Regarding the CAVE library, we feel that further optimization will cut the delay to below 5 ms. Rendering time is somewhat more fixed given the graphics hardware. The display latency is set, however, by our choice of frame rate at 48 Hz which translates to a fixed 21 ms delay.

- **Pipeline Delays**
 - ⇒ **Serial Communication**
 - ⇒ **UNIX delays**
 - ⇒ **Software delays**
- **Current lag > 100ms**
- **ScramNet connection:**
 - ⇒ **Dedicated optical fiber network**
 - ⇒ **PC to Onyx direct memory connection**
 - ⇒ **Lag expected to drop below 90 ms**

Figure 11

CAVE DIRECTIONS

A clear interest in using CAVEs for collaborative virtual prototyping over distance has been voiced by our industrial clients and researchers in national laboratories. Fortunately, many of the barriers to effective use of this elaborate form of computer-mediated teleconferencing are similar to difficulties already under examination when attempting to use remote supercomputers as simulation and database servers.

In addition, we are making the CAVE both smaller and larger (Figure 14). The ImmersaDesk™ will bring the CAVE to the size of a drafting table. The Global Information Infrastructure (GII) project will expand the size of the CAVE to that so an entire audience may experience the immersion of a virtual environment in a familiar theater format.

- **CAVE to CAVE Interaction**
 - ⇒ **Long distance cooperative VE**
 - ⇒ **Collaborative virtual prototyping**
- **ImmersaDesk**
 - ⇒ **Smaller**
 - ⇒ **Less Expensive**
- **GII/Wall**
 - ⇒ **Larger Screen Size**
 - ⇒ **Higher Resolution**
 - ⇒ **Audience Immersion**

Figure 12

CAVE-TO-CAVE ISSUES

Some of the issues that we will be exploring in this area are summarized in Figure 13. Once again, latency is the issue, and given that latency over distance is unavoidable, compensation techniques must be developed. We, at this time, know the questions regarding variable latency in the CAVE-to-CAVE or CAVE-supercomputer-CAVE model; we do not have quantitative answers. We can, however, construct actual test situations and build measurement and assessment subroutines into our libraries.

Some of the issues that we are beginning to explore are:

1. What is the peak transfer rate of polygons (triangular meshes, in practice) from shared memory of the Onyx to multiple screens, and how do various raster manager boards affect this rate?
2. What is the peak transfer rate from striped disks? How fast can we get data over local FDDI and HIPPI networks? How to use ATM networks with existing and planned hardware?
3. What happens when distance is introduced, say from Chicago to Urbana? The distance, 140 miles, is less than 1 ms away at the speed of light. Where are the delays in the existing DS3-based networking, and will the vBNS OC3/12 improve the response time as expected?
4. How can we compress the data further than triangular meshes (one triple per polygon)?
5. How much synchronization is necessary between CAVE's to provide a useful collaborative virtual prototyping capacity? What is the tradeoff between maintaining local data at each CAVE site and sharing data in real time? Does this change if a supercomputer is providing the data?

- **Minimum necessary local compute power**
- **I/O system limitations**
- **Minimum network performance**
- **Latency vs. network state**
- **Optimal data compression**
- **Synchronization between CAVE's**
- **Maintaining local data at each CAVE site**

Figure 13

IMMERSADESK

We are developing ways to make the CAVE both smaller and more affordable. The “ImmersaDesk” is a drafting-table format virtual prototyping device (characteristics summarized in Figure 14). Using stereo glasses and sonic head and hand tracking, this projection-based system offers a type of virtual reality that is semi-immersive. Rather than surrounding the user with graphics and blocking out the real world, the ImmersaDesk features a 4x5' rear-projected screen at a 45° angle. The size and position of the screen give a sufficiently wide-angle view and the ability to look down as well as forward. The resolution is 1024 x 768 at 96Hz. It will also work in non-stereo mode at 1280 x 1024 at 60Hz.

We have learned from working with the CAVE that immersion is critical to achieving a workable virtual reality/prototyping system, and that immersion is dependent on being able to look forward and down at the display in such a way that the edges of the screen are not seen, or at least not prominent. Head-tracked stereo is important for virtual reality as well, although this can be easily achieved with a high-end workstation, desktop monitor and active stereo glasses. The ImmersaDesk allows the necessary wide angle of view and, because of its screen angle, the capability to portray forward and down views on one screen. Many researchers have developed stereo, even head-tracked monitor and projection-based wall virtual reality systems, but these do not allow down views and typically have narrow angles of view.

The ImmersaDesk is a derivative of the CAVE system, being an excellent development environment for the CAVE, and also a stand-alone system. The ImmersaDesk prototype is 100% software compatible with the CAVE libraries and interfaces to software packages like Sense8's World ToolKit and SGI's Performer/Inventor, as well as visualization packages like AVS and IBM Data Explorer. Interfaces to industry standard CAD output files are also provided via these packages.

Since the CAVE/ImmersaDesk libraries have been much used to view high-bandwidth supercomputer output, the VTC/networking features will also permit the interactive shared steering of computations and the querying of databases by a number of people. This neatly combines the best of video communications with the best of simulation computing and the high-end of virtual reality interactive 3D visualization.

- **Drafting-table format**
- **Relatively small: 6' x 8' footprint**
- **Requires:**
 - ⇒ **Single pipe Onyx**
 - ⇒ **One projector**
 - ⇒ **No Architectural Modifications**
 - ⇒ **compatible with CAVE lib**
- **Interfaces to:**
 - ⇒ **Sense8's World Toolkit**
 - ⇒ **SGI Performer/Inventor**
 - ⇒ **CAD output files**

Figure 14

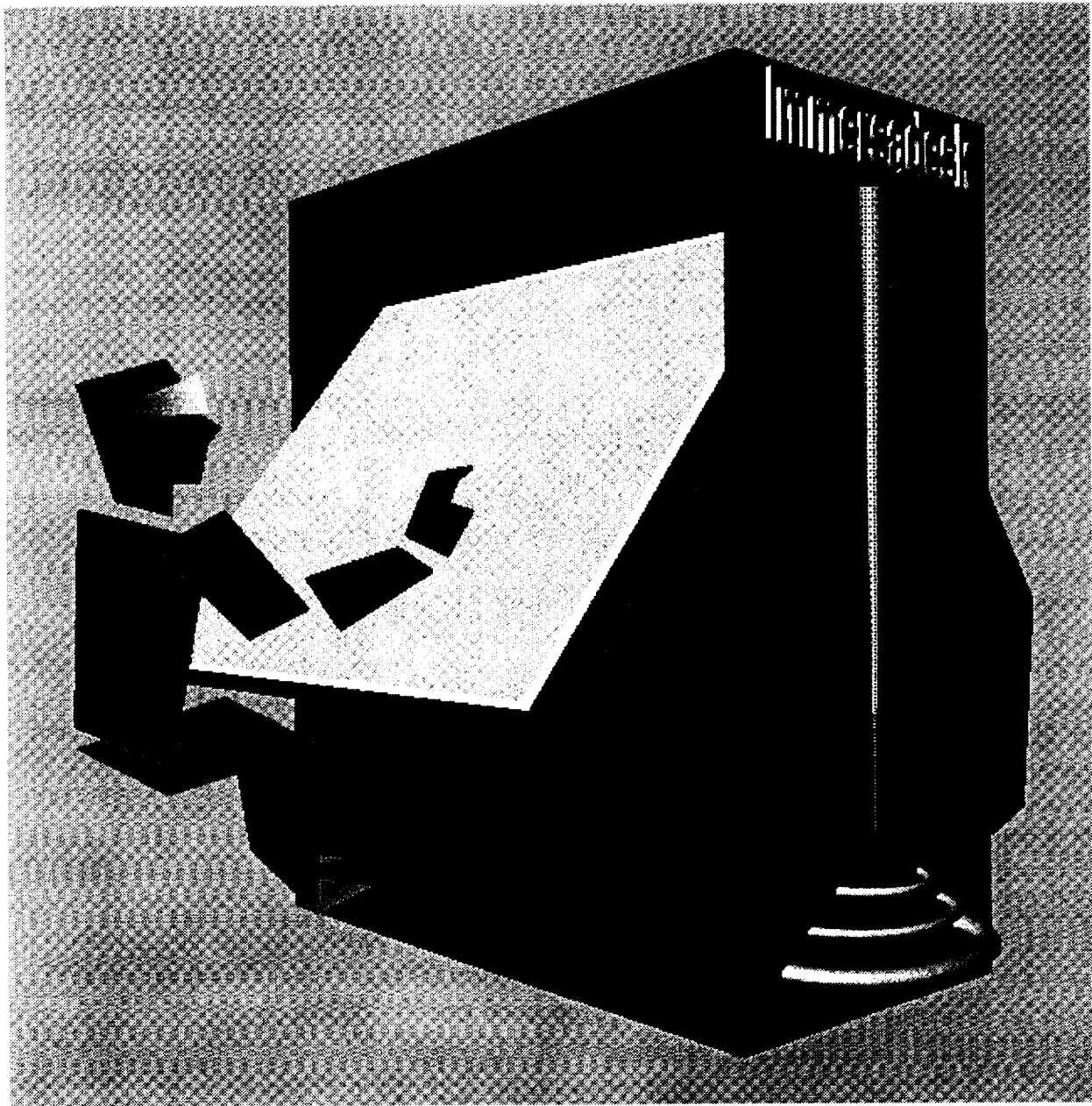


Figure 15. The ImmersaDesk. The user is seated in front of the slanted screen (left of the figure) and wearing stereo shutter glasses to obtain 3-D images. The projector and optics are contained within the box holding up the projection screen.

GII/WALL

The Super Computing'95 Global Information Infrastructure (GII) Testbed event provides a venue for inter-active 2D and 3D demonstrations of National Challenges and Grand Challenges – remotely computed in a scientist's numerical laboratory and then transmitted over high-speed networks for presentation in San Diego. The characteristics of this large format CAVE is outlined in Figure 15.

The GII/Wall is a large-screen, high-resolution (1600 x 2048) stereo projection display. A non-stereo PowerWall was developed by Paul Woodward's group at the Army High Performance Computer Research Center at University of Minnesota for the Silicon Graphics' booth at SC'94.

The GII/Wall uses four Reality Engines spread across two Power Onyxes to achieve high-resolution, high-intensity, passive-stereo images. One Onyx controls the top half of the screen and the other controls the bottom half (each at 1600 x 1024). The top and bottom are each driven by two Reality Engines displaying polarized projected images for each eye. Throwaway polarized glasses can be used by the audience instead of the active stereo glasses used in the CAVE and ImmersaDesk systems. The GII/Wall is much more suited for audiences, and although it uses a lot of computers and projectors, the number of people it reaches per unit time is far greater than either the CAVE or the ImmersaDesk.

The GII/Wall achieves its immersion by wide-screen projection, but does not allow, unfortunately, a way to look down, a problem with any normal audience seating arrangement. (Note that the angle of Omnimax/ Imax theater seating addresses this problem by steeply pitched seating). The developers are currently experimenting with large-area types of tracking, mindful of the fact that it is only possible to track one person at a time, not an audience. The GII/Wall is appropriate for applications in which high-resolution telepresence is the goal rather than audience participation.

- **Goal:**
 - ⇒ **High resolution telepresence for large audiences**
 - ⇒ **Not for audience participation**
- **Large Screen/Wall Viewing**
- **High Resolution (1600 x 2048)**
- **High Intensity (lightvalves)**
- **Passive Stereo**
- **2 Power Onyxes:**
 - ⇒ **Each with 2 SGI Reality Engines**
 - **One Onyx Each for top and bottom image**
- **Networked scaleable computing**

Figure 16

SUMMARY

In summary, an alternate form of a Virtual Environment presentation system has been described. The general characteristics of its visual, auditory, tracking, and image generation systems have been detailed. Specific problems associated with this system have been addressed and effective solutions have been shown.

In addition, two derivatives of this system have been presented: The ImmersaDesk(TM) and the Global Information Infrastructure Wall. The first represents a smaller, less expensive, multi-person immersive system. The second, a larger, audience style, presentation format of an immersive environment.

Finally, interconnection of all these VE systems was discussed with the goal of collaborative virtual prototyping for science and industry.

