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Future Directions in Visual Display Systems

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Introduction

Visual displays have evolved in several parallel application areas including television, computer monitors, graphics monitors, portable displays, projection displays and most recently, immersive displays. Film too has matured as the highest resolution display medium available. One might mistakenly proclaim that today's visual displays produce an image quality which nearly matches that of our perception. The truth is that primitive cave petroglyphs viewed in firelight far exceed the visual capacity of any modern imaging and display system. Our visual displays only represent a small piece of what our eyes perceive to be reality.

Consider the visual content in a highly ornate architectural space such as the Sistine Chapel. One is immersed within great columns, arches and a ceiling covered with Michelangelo's paintings containing hundreds of human figures. One could argue that this space is a vast immersive display system designed to invoke a sense of awe and communicate a biblical world view. The environment is static, but viewing it involves a great deal of eye, head and body motion. Even our best large-format film displays are at a loss to reproduce the range of colors, dynamic range of intensities, field of view, and level of detail present in such a space.

Visual displays are arguably becoming our primary means of information delivery. Their design can profoundly affect how we daily communicate and interact with information. As image capture, generation and display technologies advance, we will see visual systems improve in both realism and level of immersion. Arrayed display systems are already providing a leap in simultaneous wide field-of-view and high resolution. These advances are fundamentally changing the way in which information can be represented by increasing information bandwidth and enabling a deeper engagement of our visual senses.

Social Impact

Despite their inability to thoroughly feed our hungry senses, advances in display technologies, coupled with advances in high speed networking and computing, are having major impacts on society. Never before have so many ideas, philosophies, images and data been accessible to so many people worldwide.

Those of us in medium- and high-income nations are becoming increasingly empowered to express ourselves through visual media. A home video can now be shot, edited and distributed to other family members to be viewed on their television set, or digitized and uploaded onto a web page. Visual media technologies are growing less expensive and will eventually reach all corners of the earth and all levels of society. Humanities' ability to personally record, manipulate, generate, distribute and display graphic material is rapidly increasing.

Unlike television, personal media production and networking are bidirectional and tremendously empowering. Many have likened the effect to neurons connecting to form an organism, a kind of global consciousness. Some futurists, such as Interval Research's Marc Davis, even suggest that readily accessible "garage cinema" will produce a monumental change in how we communicate. He predicts an eventual shift from glottographic (vocal-based) communication to semasiographic (meaning-based) communication through images and image sequences [1]. Others are quick to point out the pitfalls of image-based communication [2]. The growing field of Information Visualization is perhaps the first formalized step towards semasiographic communication [3].

Visual Display as Human-Machine Interface

Visual displays were born out of a desire to capture, transmit, and display real-world imagery. Computers now employ visual displays as human-machine interfaces (HMIs). Achieving a better representation of real-world imagery drives display technology in essentially the same direction as achieving a better HMI. That is because both applications require an interface which exploits natural vision perception, whether it is real-world imagery or a spatial representation of data such as a graphical user interface (GUI).

Consider the visual display as a wideband HMI. The eye takes in gigabits of information per second using over 100 million photoreceptors. This information is compressed down to just a few Mbps in the retina and sent to the visual cortex [4] and other brain centers which control orientation and motor control [5]. On the other side of the interface, a computer is whirring with billions of operations per second. The object, it would seem, is to provide the highest bandwidth interface between brain and computer. To an engineer the optimal hardware solution seems obvious: total retinal stimulation. Don't let a single nerve ending in either eye go to waste.

Much of our cognitive information is derived from a small portion of our visual field-of-view (FOV). The fovial region of the eye, less than 2 degrees of our total FOV, contains most of our photoreceptors (Fig. 1). Consider the broadcast television display. Viewed from a comfortable distance it spans 10-15° of our FOV with 152,000 effective pixels of information [6].

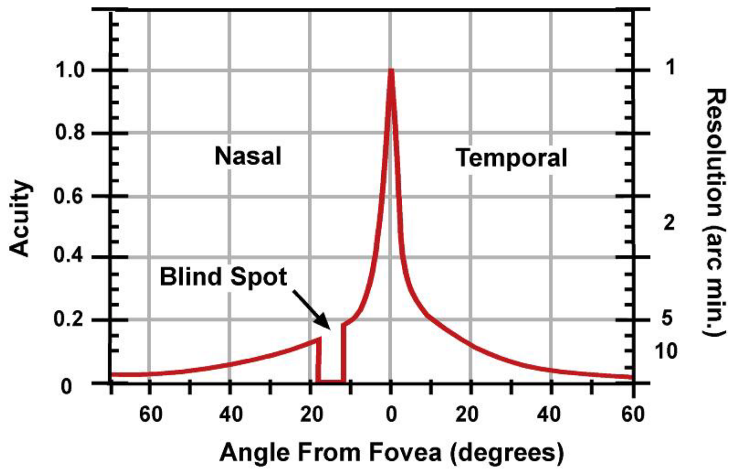


Fig. 1 - Distribution of visual acuity across the retina [21].

It doesn't take a cognitive scientist to see that there is more to our visual perception than is stimulated by staring at a television. For instance, eye and head motion allow us to take in significantly more information, providing a cognitive "view sphere" of our surroundings [7]. Cognitive maps arise when we navigate through a space providing us with a continuous stream of view spheres. Head displacement and navigation also create optic flow and motion parallax which is sensed by our peripheral vision and used by our sensory-motor system to judge motion. Motion sickness is likely an example of visual motion cues conflicting with vestibular and kinesthetic cues [8].

Ideally we want a display which can stimulate all of our retina while allowing freedom of eye rotation, head rotation, and physical displacement. Enter the head-mounted display (HMD) pioneered by Ivan Sutherland in the late 1960's [9]. This revolutionary display is coupled to the user's head. A geometrically correct computer generated image is displayed as a function of head rotation and displacement. The HMD has matured with numerous commercially available models ranging from inexpensive video game units to million-dollar helmet-mounted simulator display systems for military training [10].

Why Doesn't Everyone Use an HMD?

If the HMD is the ultimate display device, then why doesn't everyone use one? To start with, there is relatively little content available in an immersive (3D computer graphics or immersive video) format. Full-motion immersive video imaging has only recently emerged [11-13]. Synthetic 3D imagery can be generated and displayed in real time, but virtual environment (VE) technology is in its infancy. There is much to learn about representing information and telling compelling stories in three-dimensional interactive space [14]. Also, the greatest hindrance with VE technology is the high cost of a quality image generator (IG) and associated VE production. These limitations are disappearing, however, with falling computer costs and increasing graphics power.

We then have the problems associated with the displays themselves. Only very expensive HMD's can simultaneously display high resolution and wide field-of-view. Most of these units are CRT-based which means they are quite large and encumbering.

HMD's are also limited to a single user per graphics channel. Other remaining problems include multi-user hygiene and user fatigue due to improperly adjusted optics, conflicting accommodation and vergence cues, and image latency. Also, features such as opacity (the blocking out of external reality) can actually be a hindrance in real-world applications that include co-workers and ringing phones.

Head-coupled displays such as the Boom™ or Push™, pioneered by Fakespace, are common alternatives to the classic HMD [15]. See-through HMD designs, as pioneered by Virtual i-O and others, are also gaining popularity. These displays are vital to augmented reality which overlays the real world with related information [16], and will likely be popular with future wearable computers.

Another promising HMD technology is the Virtual Retinal Display (VRD) currently being refined by University of Washington's Human Interface Technology Lab. The VRD scans an image directly onto the viewer's retina resulting in images with high brightness, resolution and contrast. Still in development, the current implementation is bulky due to the optical scanner, and has a narrow exit pupil making it difficult to align one's eye to the display [17]. However, this technology could ultimately offer a low cost, high-resolution, high-brightness stereo display in a package the size of conventional eyeglasses.

The HMD is theoretically the ultimate display device. In reality, HMD technology requires greater refinement if it is to be a widespread household or office tool. Nevertheless HMD's have already found niches in applications such as entertainment, training, and visualization. HMD technology is steadily improving thanks to a number of innovative and responsible manufacturers. At last count there were over 40 HMD models offered by 23 manufacturers [18]. It is reasonable to believe that these niches will expand as HMD and computer-generated imagery (CGI) technologies mature.

Desktop Immersion: Larger Monitors?

The HMD and talk of creating a "virtual reality" popularized the concept of visual immersion. By filling our field-of-view with CGI, perhaps we could simulate reality well enough to be believable, or at least well enough to foster a "willing suspension of disbelief." VR developers see the HMD as the ultimate visual display since it would allow total freedom of head rotation, physical mobility, and direct hand-eye interaction within a virtual environment. But consider a modern office environment, boardroom, or small theater where none of these interface requirements are paramount. High-resolution monitors are already used for stereoscopic viewing using eye-sequential glasses [19]. *Why not simply make a larger monitor to cover more of our retina and forget the VR interface?*

In fact, workstation monitors have been driven to higher and higher resolutions by the needs of CAD, graphic arts, image processing, and other specialized fields. Monitors that display 1280x1024 pixels are now routine, 1600x1200 is readily available, and

2048x1536 is available but expensive. Monitors with 2048x2048 or 2560x2048 pixels currently represent the upper limit of display resolution [20].

Two important factors in immersive display design are resolution and field of view (FOV). Image fidelity requires high resolution, measured in resolvable dots or effective pixels. Immersion requires wide FOV. Increasing FOV while maintaining high resolution requires an increase in effective pixels.

The average human eye can resolve approximately 1 line-pair per arc-minute under the best viewing conditions. Viewed at a distance of 61 cm (2 feet), this represents an acuity of about 300 dots-per-inch (dpi). A 61 cm (24-inch) diagonal monitor would therefore require about 5700 horizontal dots to display eye-limited resolution. Most color monitors have 72 dpi. Therefore, a factor-of-four resolution increase is ultimately possible without making the monitor any larger. Present CRT shadow mask technology limits the spatial resolution to about 88 dpi in advanced displays [20]. Fortunately, we do not require eye-limited resolution to make an effective display.

A 61 cm (24-inch) monitor subtends about 43 degrees horizontal FOV when viewed at two feet. The horizontal FOV for both eyes is an approximate ellipse that is 130 degrees vertical by 200 degrees horizontal (Fig. 2) [21]. Add head motion and our horizontal field extends to over 270 degrees. It is easy to see how little a monitor fills our visual field. Even if we made our monitor infinitely large, it would only fill a 180-degree FOV. I call this the IMAX® limit - the FOV of a very large flat view plane.

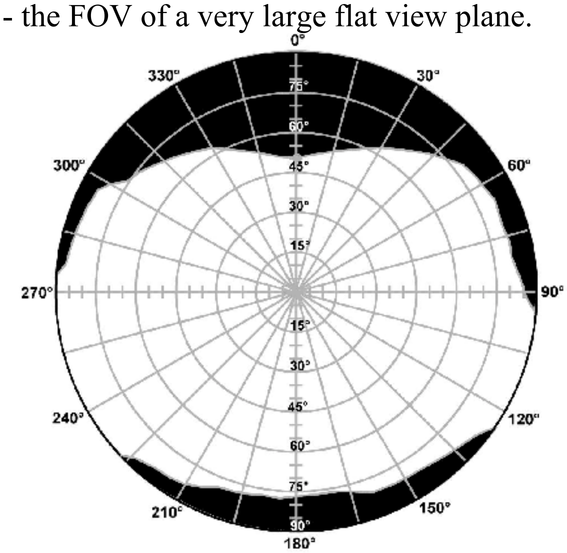
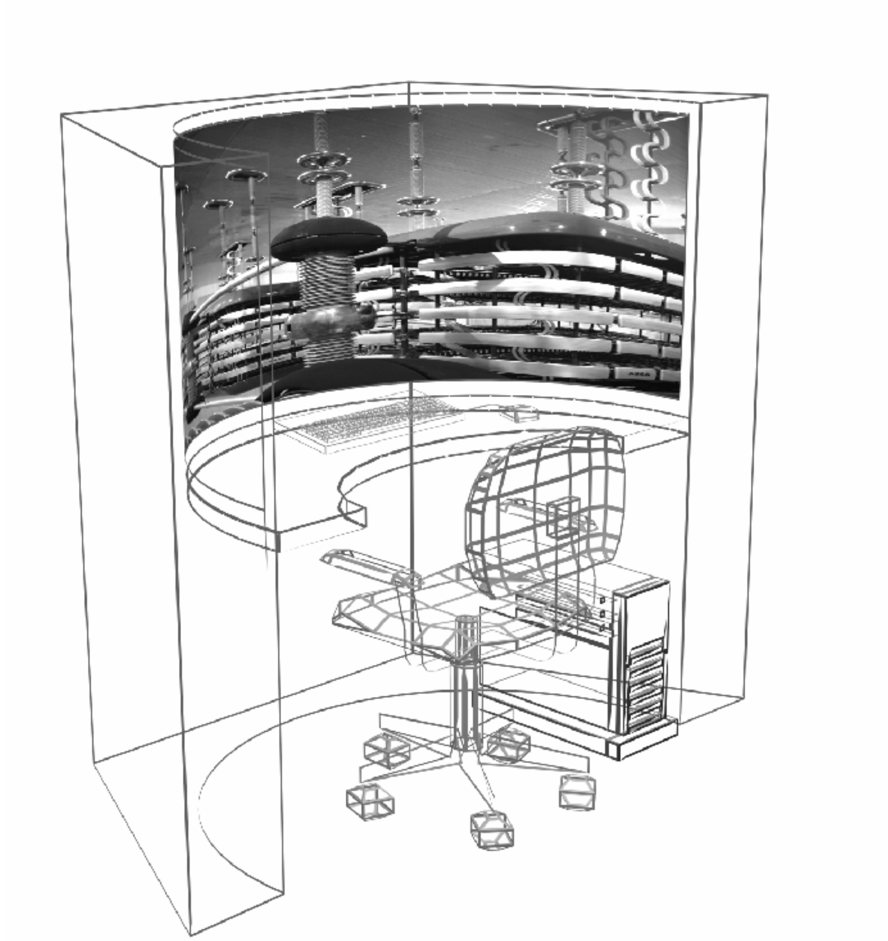


Fig. 2 - Visual field-of-view (FOV) for both eyes [21].

Let's say, however, we wrap our monitor around us in the form of a cylinder to fill a 200 degree FOV while maintaining typical monitor resolution. With a 24-inch viewing distance and 72-dpi resolution we would ideally require 6032 horizontal dots. If our cylindrical display also covered 130 degrees vertical it would be over 8-feet tall and have 7400 effective vertical pixels! Our immersive display would require an image generator that drives about 45 million effective pixels on a cylindrical surface with a 2.7 GHz video bandwidth. Today's best CRT monitors only have 5.2 million pixels and 300 MHz bandwidth.



This simple exercise demonstrates the difficulty of creating an immersive display with simultaneous wide FOV and high resolution. Enter human factors engineering. Since we are surface dwellers, our visual cognition has evolved to be much more sensitive to motion in the horizontal plane. Limiting the vertical FOV to 60 degrees gives us a vertical screen height of 28 inches with 2000 vertical resolvable dots. Our visual compromise yields a more feasible desktop display, but still requires 12 million pixels and 720 MHz bandwidth.

Arrayed Projection Displays

Our cylindrical monitor requires a 6032x2000 resolvable dot display. We also found that the largest CRT displays have only 2560x2048 addressable pixels. If we are to display a seamless, high-resolution, wide FOV image with today's technology, another approach must be adopted. Such a display is possible using arrayed projection techniques developed originally for training simulator displays. Multiple projected images are overlapped and "edge-blended" using optical or electronic means. Arrayed projection (also called mosaicking or tiling) is used to create high-resolution video displays on both flat and curved screen surfaces (Fig. 3) [22].

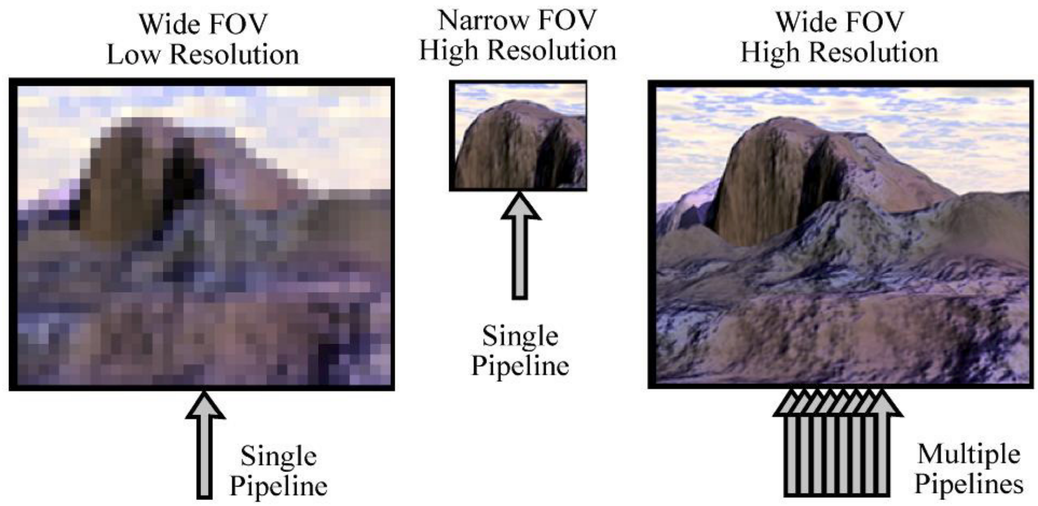


Fig. 3 - Arrayed projection allows simultaneous wide field of view and high resolution.

The importance of arrayed projection will grow with the demand for higher resolutions. This is because the laws of physics will ultimately limit the electrical bandwidth obtainable from a single video stream. Parallelism in video streams is inevitable. Multi-port video capability is now common even on desktop computers. Multiple graphics rendering pipelines are available on higher-end supercomputers. Lacking are affordable arrayed projection systems to exploit this existing capability, and the software to drive them. Companies such as Panoram, Seos, and Spitz are making great strides in these areas, but greater support from computer manufacturers will be required to produce an integrated arrayed desktop environment

Stationary Immersive Displays: VR for the Masses

The cylindrical monitor described above belongs to a class of displays sometimes called walk-in immersive, panoramic, cab, simulator, spatially immersive or stationary immersive displays (SIDs), as shown in Fig. 4 [23, 24]. SIDs have a long history of use, dating back to Robert Barker's large panoramic paintings in the late 16th century. Panoramic cinematography was demonstrated as early as 1900 [25]. Planetaria have used hemispheric dome screens for astronomical simulation for over 70 years [26]. Cinerama, a 146 degree FOV film projection format, flourished in the 1950's [27]. The 1962 world's fair in Seattle introduced modern 35mm hemispheric film, followed by IMAX® 70mm large screen in 1970 and IMAX® Dome (Omnimax) in 1973. Dome video projection is now commonly used in vehicle simulators [28]. Elaborate systems for tactical military aircraft training include eye-tracking coupled to steerable high-resolution area-of-interest inset displays [21].

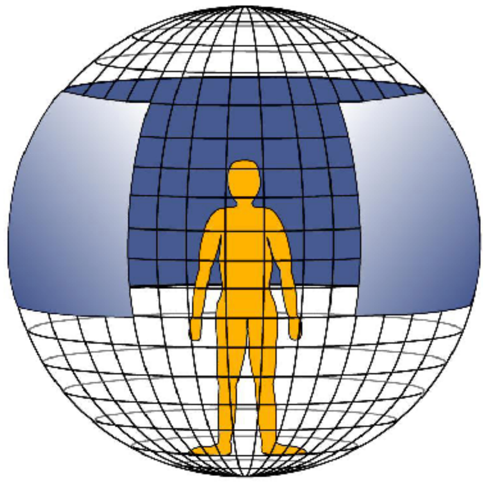


Fig. 4 - Stationary immersive display concept.

A recent SID is the CAVE, first demonstrated at SIGGRAPH 92 by the University of Illinois, Chicago [29]. The CAVE projects high-resolution stereoscopic video, refreshed at 120 Hz, onto three walls and the floor of a cubic space. The result is an immersive display with far greater resolution than an HMD. The CAVE is an interactive virtual environment (VE) system, allowing the user some degree of mobility while dynamically adjusting the rendered image perspective to the user's eyepoint. Unfortunately, direct hand-eye interaction with the VE is problematic since the user's eyes can not simultaneously focus on screen and hand. This is generally not a hindrance, as hand controllers are easily used to interact with the VE.

More recent examples of SIDs include Silicon Graphics' Reality Centre, the brainchild of David Hughes of the Reading, England branch. A similar system was installed at SGI's Mountain View headquarters where it is better known as the Visionarium [30]. The Visionarium is an 8-meter diameter partial dome screen providing 160° horizontal FOV and 40° vertical FOV. It is based on SEOS's PRODAS simulator technology and is driven by a three-pipeline SGI Onyx®. A portable Visionarium system, the GVR120, is manufactured by Panoram Technologies, Inc. (Fig. 5). Also driven in real-time by an Onyx, the GVR120 has a 120°-160° FOV and utilizes a portable 5-meter diameter cylindrical screen with three Ampro 3600 projectors. These systems are finding favor with plant and automobile designers who can realize large cost savings by finding design flaws prior to construction.

Figure 5. GVR120 Portable Visionarium by Panoram Technologies

A larger SID system for edutainment is the ElectricHorizon™ VR Theater manufactured by Spitz, Inc. (Fig. 6) [24]. This theater seats 32 persons on an inclined seating deck and

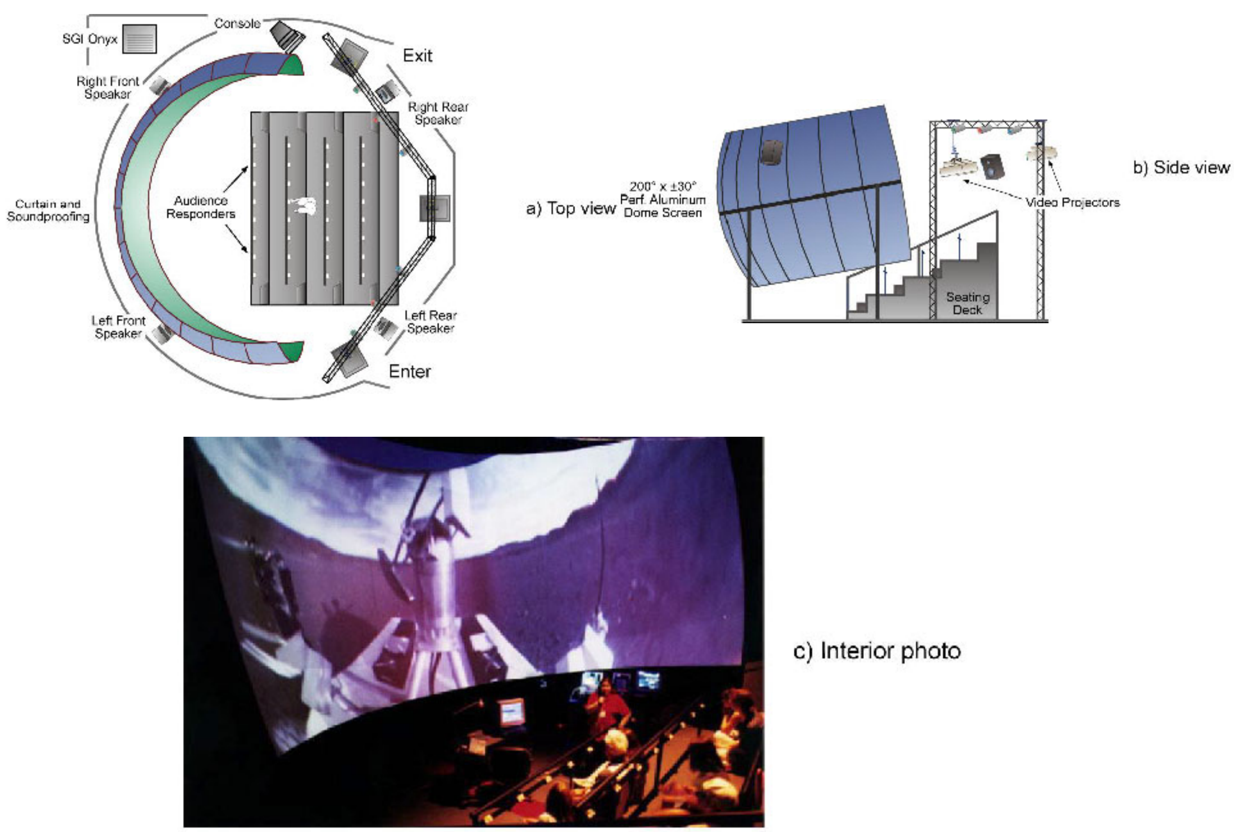


Fig. 6 - ElectricHorizon™ VR Theater at Carnegie Science Center, Pittsburgh.

includes 3-button audience responder units for interactivity. The screen is an ultra-wide 200° horizontal by 60° vertical FOV and is 8.5 meters in diameter. The image is produced by three edge-blended Electrohome Marquee™ projectors. ElectricHorizon opened in January 1997 at Pittsburgh's Carnegie Science Center as a traveling exhibit. The opening show, ROBOTIX Mars Mission, was developed by Carnegie Mellon's SIMLAB and funded by Learning Curve Toys of Chicago, IL. The show depicts a mission to the planet Mars based on Learning Curve's ROBOTIX toys and NASA Mars data sets.

The Flostation by Flogiston Corp. is a single-user SID (Fig. 7). This device uses a single hemispheric rear-projection screen onto which spherically corrected video is projected to provide full visual immersion in look-ahead mode. Originally developed under a NASA contract, the unit includes a Personal Motion Platform chair to simulate the neutral body posture and motion experienced in microgravity.

Even larger SIDs are now available for planetaria and dome theaters. Three products on the market now include Spitz's ElectricSky™, Evans & Sutherland's StarRider™, and Goto Optical's Virtuarium™ (Fig. 8). These "digital dome theaters" can navigate visitors through the virtual environment of their choice. Audience interactivity is provided by individual chair-mounted or hand-held responders or an interactive human "navigator." In one envisioned scenario, the navigator is a sports announcer who guides the passive audience's view of a real-time game between two teams engaged in VE "cyber-sports." Team members use HMD's and other specialized interface devices far too encumbering for a general audience. Such systems are the dawn of "VR for the masses."

Fig. 8 - Digital Domes: VR for the Masses

Armchair VR

We return to the argument that many real-world display applications could use the visual immersion of a CAVE, but do not require the expensive VR interface paradigm of head-tracking and data gloves. Enter a compromise in VE interface which I call Armchair VR. Using a wide FOV SID, the user remains comfortably seated and navigates the virtual space using common hand controllers or even a mouse. The effect is one of being seated in the control bridge of a large robot or exoskeleton that can be manipulated by hand controls. Such a system could even employ a separate monitor on the robot control panel for status and information display. This is similar in principle to "cab" displays used in location-based entertainment such as the BattleTech Center in Chicago [31] and various other simulator rides.

We are comfortable with cab-type environments. They are unencumbering and allow collaborative interaction. Driving a car is perhaps the most common example. Some head motion is required, but most of our time is spent looking forward and exercising our peripheral vision. Imagine trying to drive a car with all the windows painted black except for a small monitor-sized aperture on your windshield. VR systems attempting to utilize a single monitor or projection screen with stereoscopic viewing share this difficulty. Armchair VR attempts to do away with the cab and create the illusion of floating in space.

In Armchair VR, eye motion is supported by the display FOV but extensive head rotation is not. This may seem at first to be a hindrance to creating a sense of presence, the goal of most VEs. However, those who are fielding HMD systems in public venues are finding that visitors often do not exploit the range of head motion available to them [14]. Experiments in a 360-degree classroom with swivel chairs yielded similar results [32]. It seems that, in our television-based society, people prefer to sit back and be passively entertained without the effort of head and body motion.

Single-user Armchair VR systems could employ the 200°x60° cylindrical monitor display envisioned above. Larger projected video displays could seat tens or even hundreds of viewers. The use of cylindrical or dome displays allows off-axis viewing with a minimum of distortion. Unlike the rectilinear CAVE display, curved-screen displays exhibit a graceful degradation in orthoscopy as the viewer is displaced from the ideal view point. Unfortunately, most CGI rendering engines are still stuck in the "flat-plane" mentality. Images must first be rendered onto a view-plane then geometrically processed either in software or hardware for curved-surface projection. Perspective projection and rendering onto a generalized view-surface would open the door to single-pass, ultra-wide FOV rendering for spherical or cylindrical projection.

Many who are pioneering VR applications in industrial, marketing, visualization, education, entertainment and research markets believe that SID is the future display of choice for a broad range of VR-like applications. Non-VR applications requiring visualization, data navigation, or even word processing will likely benefit from the increased field-of-view as well. SIDs can readily display pre-rendered or live-action imagery without the need of a computer. One could envision a time when all home entertainment systems include a wrap-around screen.

Virtual Model Displays

Another class of displays are emerging from "Fishtank VR," the use of desktop monitors to display virtual environments [33]. Virtual Model Displays (VMDs), as dubbed by Bryson and Bolas at last year's SIGGRAPH panel [23], are limited FOV displays best suited for displaying 3D objects or models. In VEs, one is sometimes concerned more with a particular object or model than an immersive space. For instance, in a medical simulation, one might be more interested in representing the virtual patient alone. There is no need to render ceiling, walls, floor, etc. In addition to increased modeling time and system performance requirements, representing an immersive VE in such cases can actually distract the user from performing the desired task and from collaborating with others. Total engagement of the user's visual senses, with associated risk of "simulator sickness," is not always justified.

Examples of VMDs include the Electronic Visualization Laboratories' ImmersaDesk™, GMD's Responsive Workbench, and Fakespace's Immersive Workbench. While these displays can and are used to display navigable VE's, they are ideally suited for manipulation and display of 3D models and other limited FOV content that is unaffected by a display frame. Other VMDs include volumetric and globe-type displays.

Film Still Rules

As far as image brightness, resolution, dynamic range and color saturation are concerned, film still rules supreme. Large-frame formats such as 8-70 (8 perforation tall image on 70 mm frame) or 15-70 (Imax's horizontal 15 perforation format) are difficult to compete with using conventional video projection. IMAX® 3D™ is perhaps the crowning achievement of imaging and display systems [34]. Film's shortcomings, however, are its expense and lack of interactivity. Video is a much less expensive, faster turn-around production medium. Information can be downloaded from a web site daily and dropped into a show or be displayed in real time. Also, video allows real-time multi-user interactivity using, for instance, the Cinematrix™ system demonstrated at SIGGRAPH 91 and 94. The distribution of film is also a major expense. Video cinema will utilize wideband networked communications to distribute video movies.

It is not a matter of whether video projection will replace film, but a matter of when. Rapidly maturing technologies such as TI's digital micromirror device (DMD), light valve projectors, and laser video projectors are already closing in on 35mm film. Video projectors are steadily improving in brightness, contrast, and resolution, and can now be arrayed for increased resolution. Video does not exhibit film artifacts such as dust, scratches, image jitter, or image fade. Video can also be stored in digitized format which does not have the lifetime limitations of film, and which can be duplicated indefinitely without additional image degradation. Emerging video formats using progressive scan are free of the motion and edge-crawl artifacts found in interlaced NTSC and PAL. Even as “bad” as it is, existing video formats can be line-doubled or quadrupled with motion processing and detail enhancement. Such processing, popular with home theater aficionados, allows a high resolution projector to produce a stunning image easily mistaken for film.

The End of the Flat Screen?

As performance increases and prices drop, wrap-around SIDs, VMDs and HMDs promise to revolutionize many segments of the display industry. However, as with all alluring technological advances, we must question their true utility. For instance, what good is visual immersion and creating a sense of presence? We know that displays which fill our peripheral vision are more engaging to our sensorymotor systems. Does this improve cognitive learning and comprehension? Surprisingly, the answer to this question remains open, even when it comes to some visual simulators [35].

To maximize cognition, visual information should be presented in a simple and understandable form. Just because we *can* display information in an immersive, stereoscopic format does not mean that we *should*. As a sensory interface, interactive, immersive formats offer greater information bandwidth. I suspect that, over time, Information Visualization researchers will discover how to exploit that bandwidth.

From an artistic standpoint, SIDs and HMDs offer the creative mind a larger canvas on which to paint. Even renaissance painter Leonardo da Vinci considered natural perspective to be spherical [36], as do some modern cognitive scientists [37]. Immersive visuals are highly compelling and psychologically engaging. As these systems become more affordable and widely available, animators will prefer to see their work displayed before an audience on ultra-wide screen immersive displays or HMDs as opposed to a television or monitor. Artistically we are entering an era of immersive, frameless graphics.

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