SPHERICAL IMAGE REPRESENTATION AND DISPLAY: A NEW PARADIGM FOR COMPUTER GRAPHICS

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Our visual senses are flooded with graphical representations of both real and imaginary scenes. Graphical representation has progressed from early petroglyphs to artwork, printed media, photography, cinema, television, and most recently, computer graphics and networked communications. These media are a major source of visual stimulation for our edification and enjoyment. There exists one common denominator with virtually all popular forms of graphical representation: They are displayed on a flat view plane. As Michael Naimark points out in his Realspace Imaging taxonomy, monoscopic imaging of a flat plane is the equivalent of looking through a viewing window with a single stationary eye [Naimark 91]. Since we cannot poke our head through the window, we are limited to a field of view of less than 180°. Despite the problems associated with representing three-dimensional space on a plane [Barbour 91] we have been driven by the limitations of our technologies.

Throughout history, there have been those who recognized the shortcomings of planar projection. Leonardo Da Vinci considered classical perspective projection to be "artificial," while the projection which best produces the image as beheld by the eye he called "Natural Perspective Projection." [Kelso 92] Da Vinci's Natural Perspective is simply the projection of the environment on to a spherical surface, with the view point fixed at the spherical origin. Unfortunately, the realization of spherical projection required the difficult task of producing graphics on a spherical surface.

With the more recent focus on immersive graphical representations, spherical perspective is being revisited. In fact, spherical representation is being touted by some cognitive scientists as a more robust model for spatial reasoning [del Pobil 93]. Applications of the spherical reference system in AI and robotics include navigation, collision detection, and the determination of three dimensional object characteristics including orientation, distance and size. The spherical paradigm is finding applications in graphical representation as evidenced by Apple's new QuickTime-VR_, Warp California's Virtual Television (VTV), and Artificial Reality's Vision Dome. Spherical projection is also becoming more viable. Vehicle simulators routinely use domed projection surfaces, as do planetariums, omni film theaters, and most recently, entertainment simulators.

Unfortunately, the technology does not yet exist to fully immerse our visual senses within an interactive spherical viewing space which matches the visual resolution of the eye. In fact, were such a display technology to exist, today's best supercomputers would be hard pressed to render the required 300-400 million pixels at 120 frames per second needed to match our visual acuity with flicker-free stereoscopic imagery [Brown 92]. With 24-bit color, that would amount to nearly one trillion bits per second effective data rate. But the technology does exist, within certain constraints, to fool the eye into believing that one is immersed within just such a space. The purpose of this course is to present techniques for creating the illusion of presence within a domed environment.

FLAT SCREEN VIEWING

Television. Consider the visual experience of watching a television. We intellectually know that we are viewing a relatively small flat screen with limited resolution and other artifacts. No attempt is made to convince viewers that the images are actually present in their living room. A 66 cm (26-inch diagonal) television viewed at two meters only occupies an 11x15 degree field of view. This is just enough to stimulate the sensitive foveal region of the eye - provided our eyes remain fixed on the CRT. For an NTSC signal, the image formed on our retina has a resolution no better than three arc-minutes per line-pair, falling short of the one arc-minute average resolution of 20:20 vision.

Despite this, our imaginations are so engaged by the characters represented by this matrix of luminescent phosphor dots that we suspend our awareness of the medium and become captivated by the story line. Perceiving cartoon animations as “real” requires even more imagination, which our minds willingly provide. Even a narrative alone, as in old-time radio storytelling, is capable of invoking visualization and strong emotional identification. It seems that our minds are hungry for guided scenarios onto which we can project imaginary dramas. This strong need for identification with characters and a plot distracts our judgment of the medium itself [Allen 93].

Cinema. Cinema provides us with larger, clearer images. However, we rarely are provided with the illusion of true presence. At the cinema we are quite aware that we are sitting in a theater watching illusionary projections. The image of a car speeding towards us does not frighten us *per se*. There are too many cues which provide us with medium awareness, including editing technique (hard cuts, etc.), frame rate artifacts, scratches and dirt on the film, and the theater setting itself. But for the purpose of storytelling, at least, we only require a good narrative with recognizable characters with which we can identify [Smith 94]. A sense of presence is not required for emotional engagement.

Stereoscopic Displays. The introduction of stereoscopic 3D effects to cinema brought us closer to a sense of presence. Binocular depth cueing allows us to better depict volume, and is particularly effective for reproducing slow moving objects within close visual range (<10m). However, other artifacts are introduced which induce a high degree of medium awareness. While binocular disparity is exploited, no method of 3D projection effectively utilizes vergence as a depth cue. Our eyes therefore remain focused at a fixed distance. Tilting the head causes a loss of convergence. These and other factors produce eye strain in many such systems when viewed for extended periods, especially in earlier versions. Also, the 3D glasses themselves are somewhat cumbersome and limit the field of view.

These problems aside, we are still faced with a projection screen with finite extent. The screen edges often “give away” the 3D effect, giving us a visual cue that our eyes are not converged on the screen. Even head-mounted displays utilize a flat view plane. Also, the LCD devices used in HMD’s have poor optical resolution. While there is considerable research being performed to advance this and other shortcomings of HMD’s, it will be a while before HMD’s can produce a believable sense of presence.

Large Screen Cinema. Several 70mm film formats have taken hold over the years which offer greater image resolution than the standard 35mm formats. This permits a theater configuration with a larger field of view projection screen. For instance, in an IMAX_ film theater, an eight-story high screen can occupy over 70° of our visual field. With steeply-pitched seating, the theater largely disappears and we are treated to greater visual immersion. Without stationary visual cues provided by the ambient setting of a theater (floors, walls, ceiling, other patrons), our minds are free to really believe that we are on a roller coaster, or flying over the grand canyon.

In fact, many large screen effects are not appreciably enhanced by stereoscopic displays. Stereopsis looses importance as a depth cue for rapidly moving objects [Murray 94], or for objects with a distance of approximately 17 meters [Rolfe 86]. Motion parallax visible in moving scenery takes the place of motion parallax due to head motion. Viewers are forced to move their head and eyes to track objects across the large field of view, giving a greater sense of presence. Also, the phenomenon of optic flow across the peripheral vision reinforces motion cues.

Rectilinear Immersion. Even a flat screen of infinite extent only provides a 180° field of view. To create greater immersion, it is a natural extension to surround the viewer with more than one screen. A recent example is the CAVE, first demonstrated at SIGGRAPH 92 by the University of Illinois, Chicago [Cruz-Neira 93]. The cave essentially uses a cube as an approximation of a sphere. High-resolution stereoscopic video, refreshed at 120 Hz, is projected onto three walls and the floor of a cubic space. Since the primary user wears a head-tracker, the planar perspective transformations are adjusted in realtime to achieve orthoscopic image reconstruction. This minimizes image discontinuities at the corners where projection surfaces meet, at least for the one person wearing the head tracker. The result is an immersive display with far greater resolution than a head-mounted display. The CAVE has become a viable VR research tool, as evidenced by its popularity at SIGGRAPH 94.

HEMISPHERIC DISPLAYS

A domed environment is the ultimate in immersive, walk-in displays [Heilig 55]. A spherical projection surface is free of discontinuities and can potentially surround the viewer with a 360° field of view. In theaters where viewers are seated unidirectionally, a hemispheric projection surface approaches full retinal stimulation, allowing for appreciable eye and head motion. Presently there are three areas of technology which must be advanced to implement an interactive, domed projection theater: projection systems, image generation hardware and software, and domed screens.

Projection Systems. To fill a hemisphere with eye-limited resolution would require about 200 million pixels. Even the world's largest film format (15-perf, 70mm) used by IMAX® DOME cannot approach the required 14,000 lines of resolution. However, the impact of full immersion seems to make up for the lack of spatial resolution. While the IMAX® format does provide the highest resolution near-hemispheric full-motion graphics presently available, film is not an interactive medium. Audience feedback devices have recently been demonstrated which would allow an entire theater to become engaged in real-time interaction with the show content. The future will demand the real-time flexibility afforded by video projection.

Spherical video projection is presently employed in vehicle simulators. For instance, a tactical flight simulator system demonstrated at the Air Force's Human Resources Laboratory in Arizona utilizes six General Electric light-valve video projectors which are mosaicked together on a dome [Reno 89]. This system demonstrated an average of 7 arc minutes per line pair resolution over a hyperhemispherical high-gain surface. Since the limiting resolution of the eye is about 1 arc minute, a higher resolution Area of Interest (AOI) projector is servo linked to a head tracker on the pilots helmet, providing a high-resolution image inset against the background. This and similar systems, while expensive, have demonstrated the feasibility of full-dome video imagery.

<u>Image Generation</u>. Flight simulator systems require, by necessity, realtime interactive 3D graphics engines, or Image Generators (IG's). For domed simulators, wide-angle background images demand multiple IG channels. Each channel must be rendered using the appropriate view angle, warped for off-axis spherical projection, and soft-edge masked for seamless mosaicking. These real-time requirements are quite demanding of current IG engines. While IG hardware continues to advance at a rapid pace, software algorithms must also be developed for spherical perspective transformation, rendering, and projector mapping.

Many new perceptual effects are possible with a true spherical perspective transformation. For instance, the view point can be pulled from the center of the view sphere to create the spherical equivalent of a zoom lens. However, published research in spherical perspective and rendering algorithms seems to have ended about ten years ago [Fetter 84]. The paradigm shift from the view plane to the view sphere, along with the associated hardware and software developments, will likely be a slow process.

<u>Domed Screens</u>. Consider what happens when a projected image scatters off the diffuse surface of a hemispheric screen. Assuming Lambertian scattering, some of the reflected light strikes the floor, walls, and seating area while the rest lands back on the dome. Scattered light striking the dome is free to reflect multiple times, subject to some attenuation upon each successive reflection. This cross-dome scatter can seriously degrade the contrast of domed projections by "washing out" the darker areas of an image.
In domed theaters, present methods of dealing with cross-dome scatter involve reducing the screen reflectivity with spectrally neutral gray paint. Since cross-scattered light is subject to two (or more) reflections, it suffers greater attenuation in proportion to the perceived image which is attenuated by the surface reflectivity only once. Image contrast ratio due to scattered light can be expressed as

$$Cr = \frac{Li-Ls}{Ls}$$

where Li is the image luminance and Ls is the luminance of the scattered light. Decreasing reflectivity R causes higher order reflection terms within Ls to drop more rapidly than the first order image reflection Li, resulting in improved contrast (i.e. Li□R, Ls□_Rn for n_2). In practice, the improvement of Cr for a lower R will depend heavily on the location and features of the projected images, with larger image sizes generally benefiting more. This is why omni film theaters have much lower reflectivities than planetariums [Skolnick 95].

The obvious disadvantage of this approach is that the image luminance Li is reduced in proportion to R. We trade off image brightness for increased contrast, since there are obvious limits to how bright an image can be made. Omni film theaters are often faced with a choice between a picture which is bright and washed out or gray and dynamic. Omni filmmakers have learned to compensate for the media by avoiding scenes with large areas of high brightness or poor contrast.

Another solution exists for increasing contrast of domed projections. Simulator systems employ screens with a specular reflectance component in addition to diffuse reflectance. The greater the specular lobe, the greater the screen "gain" relative to a Lambertian surface. For a domed screen, the result is that more light is scattered towards the center of the theater, and less is scattered back onto the dome. In tactical aircraft simulators, the pilot is confined to a small volume near the geometric center of the dome. This allows very high dome gains to be used. However, in a theater, a reduction in viewing volume means less seating area - usually not a good idea. Also, domes with gain complicate multi-projector mosaicking since image intensity is a function of projection angle and viewing position [Skolnick 94]. IMAX® has experimented with small screen gains in their IMAX SOLIDO® theaters with reportedly good success [Arthur 92]. However, without further developments, image contrast of domed projection will never match that of flat screen projection.

PLANETARIA

In 1926 the first planetarium opened to the public in Munich, Germany. A brainstorm of Carl Zeiss' engineering team, these domed theaters were designed for one purpose - to recreate the night sky. Early planetariums were expensive monuments built to honor their wealthy philanthropists. After the space race began in the late 1950's, more affordable planetaria were constructed all over the U.S. as educational classrooms for astronomy and space science. Today's planetarium/classrooms are finding it difficult to compete for educational funding. Astronomy education is performed very effectively using classroom computers, many of which can be purchased for the cost of a planetarium. A new generation of planetaria are emerging which are pioneering non-traditional use of the planetarium as an immersive, multi-sensory theater for entertainment and "edutainment."

Advanced Planetaria. These modern planetarium theaters represent the most complex and elaborate public-access graphic display systems in use today [Rider 94]. Advanced planetaria are hemispheric theaters which utilize a multitude of projection devices, including raster video, hemispheric calligraphic video, laser graphics, large-format film, multi-image, and specialized opto-mechanical projectors. When skillfully applied, the strengths of each projection system is exploited to create the illusion of presence. Within certain limitations, individual projection sources can be orchestrated as if they were a single, high resolution projection source.

Production of graphics for hemispheric theaters is more demanding than for film or video alone. Factors such as geometric distortion, cross-dome scatter, projector mosaicking (or tiling), and limited projection field-of-view must be considered. Accurate representation of planetary motion, and the seamless integration of many separate projection devices and graphics formats presents many technical challenges in real-time synchronization and control, and image registration.

<u>Planetaria vs. Simulators and Omni Theaters</u>. Planetaria have certain advantages over other users of domed environments including vehicle simulators and omni film theaters. Simulators are required to produce graphics which are generated in realtime, necessitating powerful graphics engines with lower quality rendering. The latest planetarium video projection systems utilize component level laser video disc technology such as the Sony CRV_ format with interpolation line doubling for playback. Images can therefore be rendered in non-realtime with much greater detail, but still retain some interactive qualities due to the rapid laser disc access times. Also, simulators require user inputs to be directly linked to physical models which determine and limit image characteristics such as the motion path. Planetarium shows are carefully scripted in advance, allowing the layering of complex effects sequences. These sequences or show segments can still be triggered in realtime, or used to enhance lower resolution realtime computer graphics projections.

Both simulators and omni theaters attempt to reproduce daytime outdoor scenery which causes the greatest contrast washout due to cross-dome scatter. Much of the imagery in planetariums is projected against a black background, often with stars. The low ambient light environment prevents screen washout, provides a greater illusion of depth, and tends to hide any seams or imperfections in the projection surface as well as hiding the theater itself. Also, the visual acuity of the eye is reduced at low luminance levels, thereby reducing the impact of limited projector resolution. Since objects are projected against black, insetting an image from a high-resolution, small field of view projection source is easily accomplished. Add motion control to this limited FOV projector and you have the ability to translate the image completely around the dome. This technique is used in simulators to project targets, but requires realtime masking of the background image to inset the higher resolution target image. Only the brightest stars in a planetarium will “punch through” a crisp video image, eliminating the need for masking in many cases.

<u>Lessons from Planetaria</u>. Planetaria have 70 years of experience in hemispheric projection techniques. They have taught us how to control and synchronize many complex projection systems to produce high apparent resolution over a domed screen. The most believable graphical representation of reality is probably found in the planetarium starfield. Modern optomechanical star projectors produce a visual resolution over the dome which can exceed the resolution of the eye with up to 28,000 stars. Planetaria have also brought us dazzling laser light shows, and Evans & Sutherland’s Digistar®, the world’s first hemispheric computer graphics projector.

Planetaria also teach us what not to do in a dome. Hemispheric theaters should be designed to minimize visual cues that remind us that we are in a theater. This includes the elimination of visible seams in the dome surface, noise from projection equipment, obtrusive star projectors and control consoles (which once *were* a special effect in themselves), and brightly colored furnishings. Many contemporary planetaria continue to demonstrate false visual cues which invoke medium awareness. These include raster lines, switching noise, and tape dropouts in video images, visibility of projector dark frames, free-floating images clipped by the projector frame, intense image flicker, poor image focus, and image motion control artifacts such as jitter and backlash. In all fairness to planetarians, myself included, it is often costly and time consuming to achieve the perfect illusion of presence.

APPLICATIONS IN VIRTUAL REALITY

The success of virtual reality hinges on techniques which produce a greater sense of visual immersion. Spatial reasoning requires the creation and maintenance of cognitive maps, or a spatial awareness of the environment [del Pobil 93]. We refine these cognitive maps as we navigate through our virtual environment and manipulate objects therein. Navigation or travel over terrain involves a phenomenon called optical flow by flight simulation researchers [Richards 82]. Optic flow is the movement of objects or terrain past our central fovial vision and out to the edges of our peripheral vision. It has been found that peripheral optic flow is crucial for high performance in visually demanding tasks such as tactical aircraft combat [Rolfe 86]. Wide-angle displays are therefore important in creating the sense of presence and spatial awareness sought after by VR developers.

<u>Walk-In</u> <u>Immersive</u> <u>Displays</u>. Head-mounted displays (HMD's) are a welcome departure from ordinary planar graphical representation, although they still rely on orthostereoscopic reproduction using flat LCD panels. Very wide field-of-view HMD's are currently in development [Kaiser 95]. However, walk-in immersive displays offer several advantages over HMD technologies including group viewing and interaction, wide field of view, and high resolution without restrictive headgear. This was recognized by the developers of the CAVE [Cruz-Neira 93] who opted for immersion with the more mature flat screen technology. However, images reproduced on a domed screen provide a spherical perspective which best matches our spatial perception. Within the VR community, spherical displays are still largely ignored due to their lack of resolution and expense. However, future spherical projection displays could become the norm for common VR systems.

In fact, one such system is now being introduced into the marketplace. Artificial Reality, a spin-off from the North Carolina Supercomputing Center, has just introduced the Vision Dome, a hemispheric alternative to the flatscreen monitor [Bennett 95]. Initially designed for small to medium-sized domes (< 8 meters), their system accepts output from a computer workstation, PC, or standard video and processes it for projection on a tilted hemispheric screen. The single-projector light-valve display is full color, raster-based and is capable of stereoscopic projection. Real-world applications envisioned for Vision Dome include network management, marketing, museums, and air traffic control displays. With further advancements in video display technology, spherical image generation hardware and software, and domed screens, such systems could dominate the VR marketplace.

USING THE ILLUSION OF PRESENCE

Most of the efforts in VR and display systems revolve around the technology for creating a greater illusion of presence. Let us assume that we have a display system capable of creating the visual illusion of presence. What does it offer us that cannot be provided by existing mediums?

Recall the earlier discussion on television. Television could be described as linear narrative-based storytelling supplemented with fovial stimulation. The narrative seems to take precedence, while the limited visual element is used to enhance the narrative, set the scenes, and control the focus of our attention. Viewing television involves visual and kinesthetic passivity. We also remain comfortably detached from the action, with the obvious awareness that we are watching a television.

Presence Demands Work. Unlike television, immersive displays require active viewing, demanding content-dependent head and eye movement. Viewer fatigue is common in omni film theaters and planetariums, which explains why these programs are around one half hour in length. VR systems induce even greater fatigue and require extensive kinesthetic involvement. Immersive displays also make it more difficult to remain safely detached. We are more likely to respond to a stimuli as if it is actually present. We therefore are subject to a greater level of stress, including involuntary fear, the sense of falling, and motion sickness. The producer thus has greater command over the participant's attention and psychological experience.

Visual Storytelling. Immersive displays will bring us visual-based storytelling supplemented with narrative. As pointed out by Mort Heilig, this is more in proportion to our natural perception (70% visual, 20% auditory, 5% olfactory, 4% tactile and 1% taste) [Heilig 55]. Visual-based storytelling will allow the creation of many new storytelling devices which are not yet possible or sufficiently effective with present visual systems. For instance, many people engage in dangerous sports and activities because of the thrill it produces. Perhaps these experiences can be recreated with sufficient visual realism to invoke the same physiological response. Also, VR systems driven by artificial intelligence technology will allow interaction with cognitive-emotional agents to create drama [Bates 92].

Consider our inner experience of thoughts, emotions, and sensations. Our subjective experience is very personal and difficult to convey semantically. This is the domain of poets, who paint images and feelings with words. But our inner experience remains largely visual. Artists can convey through visual media inner realities which cannot be spoken. Traditionally, films which contain only the artistic element, without narrative, do not hold the viewer's attention for long and are not popular. However, the illusion of immersion in an artistic environment with matching aural/musical stimulation could create a moving experience which transcends narrative. Laser light shows and music videos are perhaps the precursors of this new art form.

Another possible storytelling device is to depict archetypes representing the character's inner conflict or imagination. In other words, we would crawl into the character's head. The immersive display allows room for the simultaneous depiction of our external reality and our inner archetypes, memories, and internal imaging.

SUMMARY

Technology is emerging which will allow computer graphics to fully exploit the spherical perspective and display paradigm. The course notes which follow present the latest techniques for the generation and display of spherical graphics within existing hemispheric environments including planetaria, omni theaters, and simulators. Topics include the evolution of hemispheric theaters, technical overview of domed projection systems and environments, spherical perspective projections, and the use of hemispheric multi-image, film, video, and laser graphics to create the illusion of presence

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