The 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST (2006)
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Designing a Real-Time playback system for a Dome Theater

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Abstract
Most dome display systems today employ pre-rendered shows for attracting visitors. In addition since the technology is well established, developers have many tools at their disposal for creating such shows. On the contrary real-time shows for dome displays are just starting to appear. As a result the production of such shows is not a standardized process. Slowly, progress is made. Graphics generator cards are able to support the required SXGA+ resolutions and the supporting cluster systems are able to supply the processing power and memory bandwidth that such real-time systems require. Tools have to be developed and new processes have to be established. The Foundation of the Hellenic World (FHW) having produced numerous real-time productions for immersive flat display systems has great experience in realizing such shows. In this paper we present the technological developments for the production of real time applications for digital dome display systems.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computing Graphics]: Three-dimensional Graphics and Realism – virtual reality. I.3.2 [Computing Graphics]: Graphics Systems – distributed/network graphics. I.3.6 [Computing Graphics]: Methodology and Techniques – device independence.

1. Introduction

Curved-screen spherical projection (dome) theaters are commonly associated with planetariums and other installations that project pre-rendered content, which can be compared to movie or video setups. The final image the “Dome Master” is generated offline using specially designed video editing tools and rendering software to perform the radial projection and image stitching. Depending on the projection system, this is then processed in special vendor specific tools to separate the stream for each projector and store it on disks [EMM01]. Real-time synthesized imagery is not very common in such type of installations due to the high complexity and performance demands of the underlying system.

The real-time virtual reality (VR) dome theater of FHW, utilizes a fully digital projection system, configurable in a monoscopic, stereoscopic or a mixed mode of operation. Six pairs of seamlessly blended SXGA+ projectors project the stereo synthesized imagery on a tilted hemispherical reflective surface of 14.4m in diameter Figure 1. The auditorium is designed to host up to 132 visitors at the same time. They will be transferred into virtual worlds and enjoy a truly immersive and interactive experience.

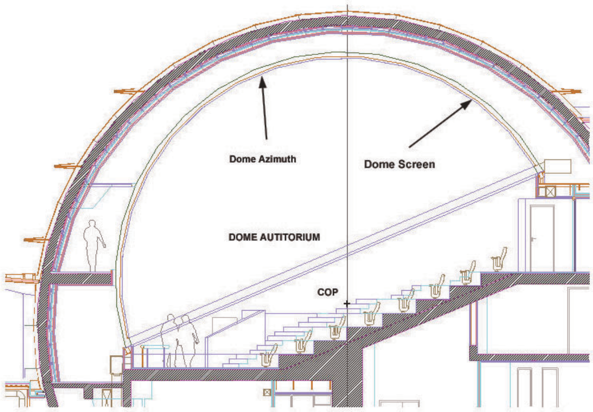

Figure 1: *The Dome Theatre of FHW. 132 seats, 14.4 m dome diagonal, 20 º of dome surface.*

During the design and implementation of the “Tholos” dome virtual reality system, many issues had to be addressed, regarding both the real-time rendering/simulation engine and the content production pipeline. These issues will be discussed in more detail in the following sections involving, the spherical projection configuration and reconfiguration, computing system architecture, the desktop production previewing tools and finally the stereoscopic display problems as well as the integration of interaction and video streams into a unified media platform.

2. Features and Benefits of Real-Time Dome Display

Today's digital domes provide impressive architectural setup and design, pre show areas, which attenuate the anticipation and prepare the visitors for the show while at the same time allow their eyes to adjust to the dark environment in the dome area. The projectors used provide high-resolution imagery on the dome surface, which covers the whole peripheral vision of its visitors. Special designed seats, tilted, with proper body support to provide comfortable view, supplement the plethora of dazzling features offering a much more exciting experience for a larger audience, fostering an increased willingness to suspend disbelief.

Additionally by incorporating controls on each seat an increased level of participation can be reached, turning each show into a performance where spectators participate actively in the unraveling story. Currently the most common way in dome for mass interaction is by employing a voting/poll system where the visitors influence the storyline by placing their votes at discrete time frames using the chair controls.

Furthermore, a real-time dome display system can combine pre-rendered and real-time graphics in a seamless manner, as well as incorporate interactive, live on-stage action. The possibilities are limitless, provided a flexible, extensible and sustainable infrastructure is properly designed and built. The ability to host large audiences make dome theaters almost ideal for demonstration purposes and large-scale visitor attractions providing greater throughput, cost effectiveness and profit sustainability.

3. Real-Time Rendering Issues

3.1. Projection Setup

Real time engines for Dome projection differ in various aspects from engines designed for standard wall projection single screen systems. The primary difficulty is the need to render to multiple tiles seamlessly providing overlap for blending. This implies the generation of multiple, overlapping off-axis (oblique) projection frusta, which correspond to the frusta from the common center of projection (COP) to the dome surface. The combination of various streams of different projectors to a unified picture is not feasible without proper alignment and hardware to cover the edges between adjacent tiles. Mechanical alignment on the projector position and calibrations are not adequate for pixel perfect transitions, which are not noticeable by the eye. Therefore projectors use special composition for stitching and warping the output streams onto the Dome surface to

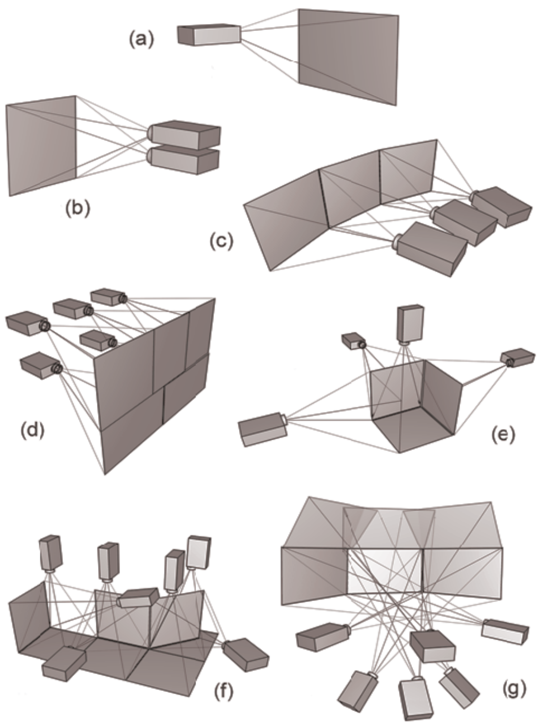

Figure 2: *Examples of display tile configurations possible with TiDE: (a) planar active stereo, (b) planar passive stereo, (c) curved-screen reality center, (d) large video wall, (e) CAVE like, (f) arbitrary topology, (g) dome.*

match their geometry and blending masks to help fade seamlessly the black levels and color image from one tile to another.

Warping and Stitching can be done either in software on the driver level as is shown in open source solutions [BOU05], [JJ05] or with external hardware. The later solution is preferred for midsize to large planetariums and was also the preferred choice for the FHW Dome because it introduces no additional software path, which might slow down the overall application and offers greater flexibility in alignment and setup.

Having all that in mind, we have implemented a display module, named TiDE (Tiled Display Environment) [GGD*06], which operates as a projection matrix configuration adapter between the actual rendering process and the graphics outputs of a system. An XML configuration file provides a list of any possible scripted configurations, defining the actual tiles in space, the COP, monoscopic or stereoscopic rendering. So the user of the system does not have to worry about frusta and display channels. If one knows the physical positioning and size of the target projection surfaces, any arbitrary view can be transparently generated see Figure 2. The FHW Dome consists of six pairs of projectors rendering in stereo with 72% field of view on the Dome surface with 20% overlap.

3.2. Computing Cluster

In order to drive a multi-display environment such as a dome, multiple graphics outputs need to be synchronized at each frame to generate partial views of the same panorama. One convenient solution, traditionally available was the purchase of shared memory multiprocessor/multi-pipe systems from custom vendors. Unfortunately these solutions are being phased out since the market and scientific community turned to cluster architecture of individual machines which provided lower cost of maintenance and upgrade, support for the latest advancements in hardware and better performance.

For powering the FHW Dome spherical display, twelve projectors and cluster PC's were chosen, each projector being powered by one machine and each pair of projectors/machines providing the stereo imagery for one of the six tiles on the surface. We have implemented an asymmetric master/slave cluster configuration, which provides a highly parallel execution and has almost zero scaling overhead (frame lag) when adding new node (see taxonomy in [ZK02]). Each node is a completely self-contained VR system, advancing at each frame according to the user and application dependent variables. However, this set of data is very small and only consists of the user interaction primitive actions (e.g. button presses, tracker input, joystick values) and a global application reference clock. The role of the master is reduced to that of a coordinator of the other nodes (slaves) and only provides synchronization for the global clock and the user input data. The above functionality, synchronization and data exchange layer is handled by an application-independent library we have developed, named EVSSyncer.

For defining the projection setup each node has its own display configuration script (XML file) using the TiDE framework described earlier and therefore knows how to render the appropriate area.

3.3 Audio Hardware

One of the most important and impressive features of digital domes is their sound design. Multiple subwoofer and stereo boxes are placed at specific positions behind the dome surface to provide immersive surround sound conforming to THX or Dolby Surround specifications. The sound software must support the setup and provide 3D sound sources and specially designed fading mechanisms for 3D panning the sound source inside the dome.

We have implemented a custom driver layer above OpenAL [OAL] for adjusting its functionality to the sound system used. A special sound subsystem PC is used to handle, playback and synchronize the sound media.

3.4 Interaction Hardware

To increase customer participation every seat has it own unique controls, which have to be collected and processed by the applications. Besides the problem of how to interpret all these data developing the interaction metaphors there is also the burden to collect it. Each seat provides a 2 axis joystick with analog values [0-1] and at least 4 buttons with discreet values [0/1]. Usually a dedicated PC handles the entire input load and communicates its result to the master.

We have implemented the same approach using a custom PC, which interfaces the input hardware and communicates the data over UDP connection to the master. The VRPN [RTC*01] framework had already this client – server architecture and software daemons and was adapted to our setup.

3.5 Video Integration

Virtual reality theaters often need to switch to analog or digital video sources in order to project pre-rendered or live captured video content. The integration of streaming video into a multiprojector display environment can be done at a physical level, by redirecting the video source to the proper projector. Although this may work fine for a planar, slightly curved or cylindrical projection surface, it is not recommended for a dome system with fixed projectors. It is more flexible to be able to control the video output without caring about the physical configuration of the projection system. This means that the same production can be played at a different theatre without any modification.

We have implemented a simple yet effective mechanism for combining external video sources from files or other sources with the 3D environment [PGC03]. All video streams are handled as textures and may be applied to any type of geometric primitive or prepared geometry with or without a blending mask. Furthermore, an input stream can be on the fly combined and synchronized with a separate alpha-value stream (e.g. from chroma keying).

4. Desktop Production Previewing Tools

The usual practice is that a full-featured VR system, that drives a show, is only installed at the exhibition/VR theater site due to the specialized computing and audiovisual hardware integrated into it. Therefore, the development of the VR engine and the creation of the production content are very frequently done on a different platform than the one the final production is targeted for. Typical single-screen graphics workstations are used for both the aforementioned tasks and the application is then tested at specific milestones in the actual VR environment (the dome here). The VR industry has resorted to providing simulators of specific commercial environments (e.g. the CAVE simulator of VRCO's CAVElib) that run on single-screen workstations to alleviate this problem. In the case of the dome of the FHW, the use of simulators was imperative since the application and content development began well before the system was installed.

Unfortunately, there were almost no platform simulators available which would work on real-time content. Such simulators exist for Caves, Walls, Curved-Tilted displays, but for domes the tools available were only suitable for pre-rendered content. Although specific providers (such as Evans and Sutherland) [DIGISTAR] do distribute such proprietary dome simulators, as closed libraries for their hardware and software system, such a solution was not considered open enough.

Provided that the real hardware setup is calibrated correctly, the final result of all masked/blended projector images is a seamless hemispherical image. It became clear that to simulate successfully such a setup with high frame count, projections should be done by the graphics hardware. Essentially what was required was to place the dome virtually inside the 3D environment and project everything onto its surface, see Figure 3d-e. Cubic Environment Mapping [GRE93] supported in OpenGL since version 1.2 and Direct3D version 9, can be used to project six rendered images onto any geometry. The 6 texture tiles images can be conveniently rendered placing the virtual camera in the COP of the Dome, and rendering the scene 6 times with the appropriate viewing transformation. These images are then projected transparently without seams onto the dome. Practical cube map implementations [SA04] result in very small texture stretching since the texture tile that is most perpendicular to the normal vector at a given point is chosen for texturing the surface.

The final implementation of the dome simulator is parametric, tilt, aperture, center of projection can be adjusted to match different setups. Another, application specific piece of functionality that was added involved the ability to simulate the vista from any of the 132 seats of the FHW dome and from arbitrary points in space. This allowed us to get a very clear idea about the apparent distortion from the visitors' point of view as can be ssen in Figure 3a-c. As the simulator is hardware-accelerated, the frame rate remains high despite the overhead of rendering the scene 6 times to produce the cubemap and it can be easily tied to any 3D graphics engine. The dome simulator provided a reliable preview mechanism and observation of various peculiarities and viewing problems of the dome production.

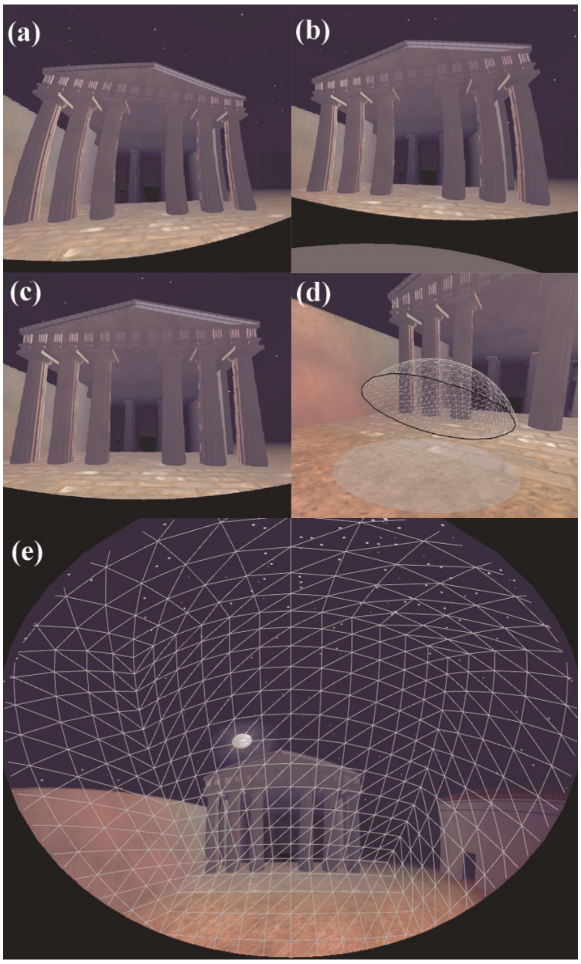

Figure 3: *The dome simulator (d-e) and resulting distortion tests. (a-b) Vantage points away from the center of projection. (c) View position in the vicinity of the center of projection.*

5. Viewing issues with respect to spherical Displays

Transferring a production pipeline from traditional wall displays to Domes introduces various problems and issues both in rendering and interaction.

5.1. Motion Magnigfication and Navigation

In Dome displays the limitations and restrictions, of high frame per second (FPS) and smooth motion, applying to real-time systems are even stricter. Because of the wide FOV, size and orientation of the display, the resulting motion magnification makes lower frame rates, even during small periods of the application, totally unacceptable. This also means that any sudden/abrupt change in the navigation introduces "cyber sickness". If control is not smooth enough the audience may feel disoriented.

Artifacts and rendering problems are also magnified and are harder to hide. In general low polygon geometry looks a lot worse than in traditional systems, which suggests that an increase of geometric quality is needed.

Useful metaphors for large audience interaction have also to be developed. Instead of 1-2 user devices an interactive dome has to handle a large amount of input data, usually equal to the amount of visitors. Currently the vote-poll mechanism is widely used but other ways of interaction are open for research. When voting-polling, each visitor has a button/joystick, which he uses to influence the storyline and feel part of it.

5.2. Stereoscopic Display

Stereoscopic viewing and depth perception in VR is achieved by generating a pair of images, one corresponding to the viewpoint of the left eye and one of the right and then directing them to the corresponding eye using simultaneous or interleaved image projection.

The established eye-separation mechanisms for non-contact viewing systems (head-mounted displays) are active and passive stereo. However, for stereo in a large dome theater, not all technologies work well. Active stereo is more expensive, not only due to the active projectors and the active stereo glasses, but also because of the high bandwidth demand on the rest of the system including image generators, interfaces, cables, switchers etc. In addition, active stereo glasses break easy so they are not suited for large public audiences. Polarization-based passive stereo also is not fitted for domes due to its narrow field of view due to possible cross-talk (ghosting) and the requirement of high gain reflective polarization-preserving screen. The Infitec™ (interference filter technology) passive stereo solution does not require special screen coating on the other hand [JF03]. Infitec™ delivers stereo separation without ghosting, with full freedom of motion, independent of head tilt. The images (left and right) arrive simultaneously from a pair of projectors. The place of the polarized filters take optical interference filters that perform a frequency division multiplexing of the stereo pair.

Full dome stereo is challenging because of the large audience volume that view the same imagery from completely different viewing angles [HOD93]. If interesting images appear at the top part of the dome and even further back then visitors continue tilting their head backwards to observe those images or they turn their head or they turn their head sideways, consult Figure 1. If polarization passive stereo is used and the head is tilted further than the optical axis of the projectors, the eye-piece filters allow the wrong polarized image to pass through, resulting in cross-eye stereo viewing, which is quite annoying. Wavelength division multiplexing is free of this problem and requires no particularly expensive or fragile glasses.

5.3. Image Distortion

The location of the center of projection (COP) for a dome production is important. The COP is the point inside the Dome around which the content is designed and where the imagery will appear geometrically correct. Usually, COP coincides with the center of the spherical surface. It is considered acceptable that even if no one is seated exactly at the COP, there is a fairly large area in its vicinity where viewing is optimal and distortion-free, like in Figure 3c. As we move further away from the COP, we perceive the intersection of a projected line segment (i.e. a plane) and the curved surface as an arch, due to our oblique relative view direction, as seen in Figure 3a-c. This problem tends to be very noticeable when displaying architectural elements or

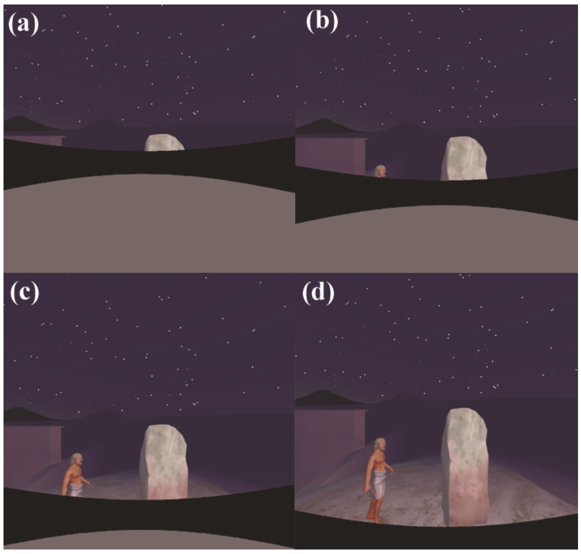

Figure 4: *Vertical Field of View, shows how much of the ground is seen by the visitor. (a) Using no tilting at all. (b) 10º tilt. (c) 20º tilt. (d) 30º tilt.*

other shapes with long straight lines and flat surfaces. The effect is further accentuated by fast motion, e.g. navigation through an archway or between pillars.

5.4. Limited Vertical Field of View

Although a dome display environment has a very large field of view (FOV) (in the case of the FHW Dome, a vertical span of 160 Degrees), it is centered close to the top of the dome. This comes in contrast to the traditional movement and setup of the camera, which points horizontally upfront where the main FOV of our eyes normally is. Existing VR installations such as CAVE-like surround screen environments or curved-wall systems provide a large FOV mainly around the horizontal direction. On the other hand, domes have a very limited FOV at the baseline (physical horizon), which makes scenes with content close to the ground or below the ground horizon difficult to visualize. A technique to alleviate this problem is to virtually shift the FOV vertically, as shown in Figure 4, by slightly tilting the virtual horizon up, applying a rotational transformation on the viewing matrices. For the same reason the dome structure is tilted by design 23 degrees downward. The cumulative effect of the physically tilted dome and the virtually lifted horizon produces an adequate FOV to convincingly visualize objects near the spectators at ground level and have a substantial part of the ground environment in view for better logical reference. A 10° tilt of the virtual horizon is in most cases acceptable but it should not be combined with a fast forward motion into the virtual world as this can cause nausea on visitors further away from the COP [LBV99].

6. Conclusions

The curved surround screen of a dome and the multi-channel display requirements impose many restrictions and problems, such as the ones we have encountered and discussed in this paper. Not all content can be equally successfully ported to a dome VR theater and special care has to be taken to adjust and rearrange the virtual environment to match the physical properties of the dome.

Nevertheless the future for real-time digital dome display looks promising. Standardized/unified interfaces for all the tools from production through to theater automation, have to be specified. Hardware specific arrangements still dominate the way the final production is to be shown. Not every animation/production house has a dome theater for production; therefore general preview tools like the one implemented at FHW for their Dome is essential to open the dome market to more users. Off the shelf 2D/3D rendering packages should adapt to that market and provide the creation of arbitrary/programmable camera projections for real-time WYSIWYG preview.

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