Interactive 3D Stereoscopic Dome with Automatic Calibration

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Abstract

In recent years, the advances in projection technology and the increasing rendering capacity of modern computers allowed the development of immersive digital domes. Digital dome systems are not limited to planetariums, but also find their way into science centers, theme parks, or multimedia events. However, most installations do not support 3D stereoscopic display, because of the difficulties the curved projection surface implies.

In this paper, we present both the construction of a small 3D stereoscopic dome and a versatile multi-projector system that exploits the capabilities digital technology offers today. Our system performs automatic geometric and color projector calibration as well as soft-edge blending. Moreover, it implements real time media compositing, which allows enhancing dome viewing experiences and going beyond the simple playout of pre-rendered content by enabling user interaction.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality

1. Introduction

Dome projections are one of the most immersive kinds of display systems, because everything around the viewer (i.e. front, sides, back and top) is covered by the projection without any disturbing corners and edges in the screen. Because of the surrounding and curved shape, dome projections enrich the viewers'perception with depth and three-dimensionality, even without the use of any 3D stereoscopic technology. Domes are mainly used in planetariums, but also find application in science centers, or for media events.

Until the end of the millennium, analogue technology has been used for the dome projection in planetariums: a device that could display stars as light points and a limited number of planets using slide projectors. In the last ten years, many planetariums successively replaced or complemented analogue technology with digital projection, using next-generation projection systems consisting of modern PCs and novel software products. Those digital solutions enable the planetarium domes to display arbitrary kinds of media (images, movies, sounds, etc.) instead of only stars and some planets. This opens up the opportunity to provide immersive realities of any kind to the viewer.

In this paper, we present our setup of a 3D stereoscopic dome built in 2009. It is unique in its small size of 4.20 meters in diameter, as most installations emphasize their large dimensions. However, many problems become relevant only when building small domes, such as space restrictions in the perimeter or acoustical problems without a perforated projection surface. Besides this, our dome is capable of displaying 3D stereoscopic content. Until now, there are only very few examples of 3D stereoscopic domes. Our software is a professional system running in several locations worldwide. We developed components of the "powerdome" fulldome planetarium system by Carl Zeiss [Sch08].

After reviewing related work in section 2, we discuss both the details of the construction of the dome and our software system in sections 3 and 4. Afterwards, we provide details on specific issues, such as geometric and color calibration (section 5), our 3D stereoscopic projection (section 6), and user interaction (section 7). Finally, we draw a conclusion and give directions for future research in section 8.

2. Related Work

As mentioned above, many planetariums are currently converting from analogue techniques to digital technologies. Some of these digital systems available at market are “DigitalSky” by Sky-Skan [Sky09], “powerdome” by Carl Zeiss [Hau08, Sch08], and “Digistar” by Evans & Sutherland

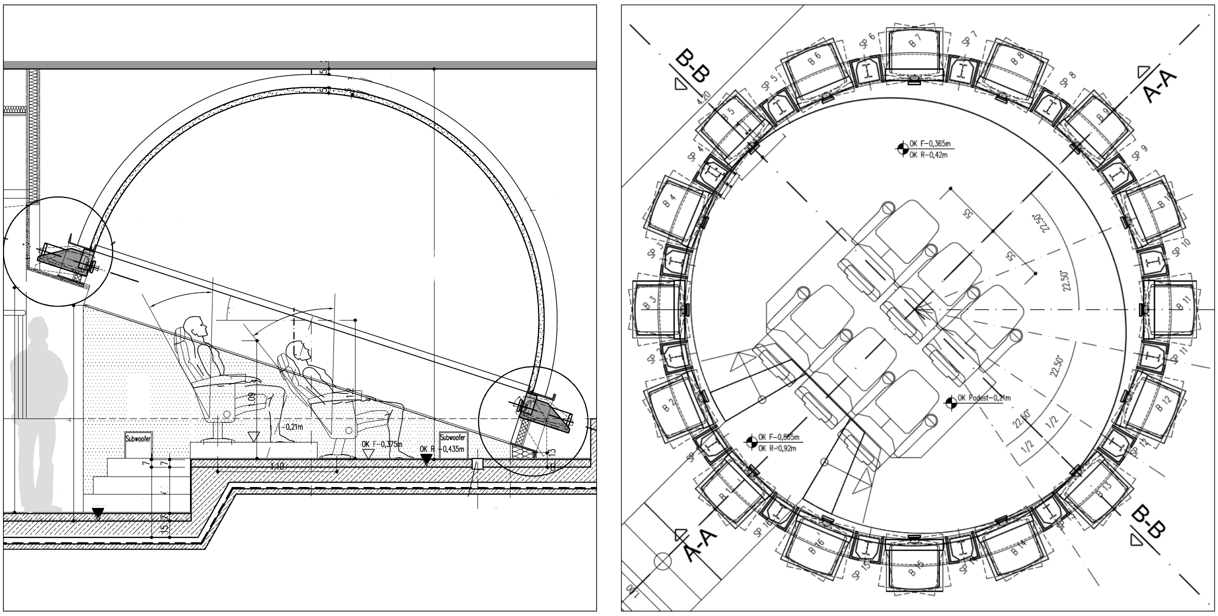

Figure 1: *The cross section (left) and floor plan (right) of our 3D stereoscopic dome. The floor plan also shows the projectors ("B1–B16") and the speakers ("SP1–SP16") in-between.*

[Eva09]. The research in this area is still ongoing, e.g. in the coupling of high-resolution dome projection and new approaches of surround sound technologies [Bru09].

Currently, there is only a very small number of dome installations that are able to display fulldome 3D stereoscopic content. In winter 2006/2007, for example, the Foundation of the Hellenic World inaugurated "Tholos", a dome-shaped virtual reality theater. The diameter is 13 meters and 12 SXGA+ projectors are used for the stereo projection [Gai06]. In January 2008, a 3D planetarium was opened at the Imiloa Astronomy Center of Hawaii. The projection is done by four Sony SXRD 4K projectors, the dome has a diameter of 16 meters [Wed08]. In December 2008, the Science Museum of Tokyo, Japan, opened the Synra Dome. It uses 12 Barco SXGA+ projectors and has a diameter of 10 meters [Bar08]. In all of these installations, Infitec filters (color comb filters with different bands) are used for separating both eyes [JF03].

3. Construction and Hardware of the Dome

As already mentioned, we built-up a small dome with 4.2 meters in diameter. It has six seats and was designed as a "home theater". Therefore, it offers an optimal solution where space is limited. This is in contrast to most other installations, which usually target large audiences. The construction plan of our dome is shown in figure 1.

In larger domes, the projection surface usually starts at about 2–3 meters. In our case, however, there is not enough space. A horizontal alignment of the dome would require the audience to lie, which is not possible due to the space limitations. Thus, the chairs we installed are more upright. Furthermore, to maintain the immersive perception, we tilted the dome by 18 degrees. This ensures the projection to cover as much as possible of the visual field of the viewers. The tilting and the angles of the chairs result in a main viewing direction of about 55 degrees above dome's the lower border.

As can be seen in figure 1 (right), there is very limited space to position all projectors and loudspeakers. For covering the entire dome, we need eight full HD (1920×1080 pixels) projectors. For the stereoscopic projection, we need a set of projectors for each eye, resulting in 16 projectors in total. In the current setup, we are using JVC DLA-HD1 projectors that are equipped with Infitec stereo filters. The system is driven by one master PC, one file server, one audio renderer, and eight PCs, each of which renders the output for two projectors.

With the full HD projectors, we achieve a resolution of about 4k x 4k pixels. On average, a pixel has a side length of 1.7mm on the dome surface, which equals 2.7 arc minutes. With a lower resolution (e.g. 2k x 2k), the visual quality would be very limited and unsatisfying.

For immersive sound experiences, we installed a "Spatial Pan" system by Fraunhofer IDMT [Rod08]. It consists of 16 speakers placed between the projectors and two subwoofers. in contrast to conventional surround sound systems, Spatial Pan uses a wave field synthesis-based algorithm. It offers a

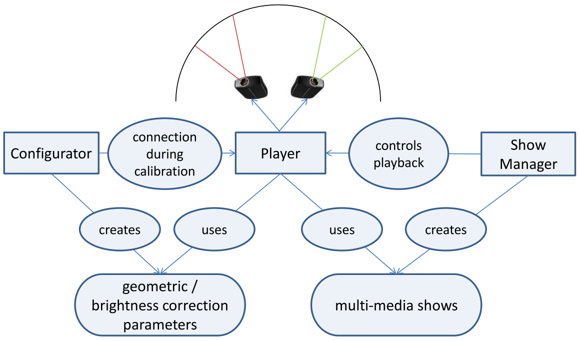

Figure 2: *Overview of major components of our software system and their relations.*

much larger sweet spot and allows positioning sound sources very accurately in 3D space.

Because of the proximity of the audience, we cannot use a perforated dome surface as it is often done in large domes. In order to reduce acoustical reflections, we decided to install a special acoustic floor and sonic absorbers at the sides that reduce the reverberation caused by inter-reflection. Besides this, the construction of the dome ensures sonic insulation in order to reduce external noises coming from the projectors or the air conditioning.

4. The Software System

Our software system consists of three major components that seamlessly play together: The "Configurator" for planning projection systems and computing blending and calibration data, the "ShowManager" for authoring media shows, and the "Player" for doing the actual play-out during a presentation. The relationship between the three components is illustrated in figure 2. In the following subsections, we provide details about each component.

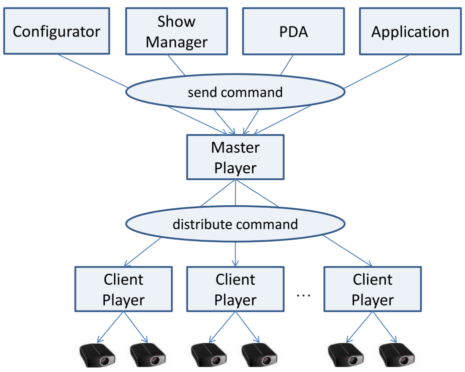

Figure 3: *Overview of distribution of commands in the cluster coming from different sources.*

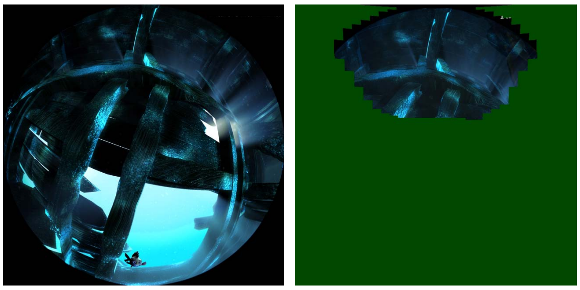

Figure 4: *Example of a partially decoded video for one projector channel. Left: fully decoded frame; right: partially decoded frame.*

4.1. The Player

The central component of our system is the Player. It displays shows in a rendering cluster. It is implemented in Visual C++ and uses Microsoft DirectShow for video and audio processing, and Microsoft Direct3D for rendering.

The cluster is organized as a master and several slaves. In our dome, each slave renders two channels (projector outputs). The master controls the whole rendering process. It receives all commands from the ShowManager or any other application via UDP and forwards them to the clients (see figure 3). The resources (images, videos, audio files, etc.) are centrally stored on a file server, from which the clients load all required resources during initialization.

During the play-out, it is crucial to maintain synchronization among all nodes in the cluster. Otherwise, mismatches between projector channels in the dome would be visible. We realize synchronization by implementing a distributed clock shared within the cluster. For this, the clocks of the slave computers are adjusted to match the clock of the master. This adjustment is done via Ethernet. All messages the master sends to the slaves are tagged with a time stamp, which ensures the simultaneous execution of commands.

With our distributed clock method, we achieve deviations of at most 100ns, which is enough for a frame synchronization without genlock. However, using a genlock is indispensable in the case of hard-edge blending (for example, if the Sony SXRD 4k projector is used). Otherwise, mismatches are still visible.

Our rendering is based on media compositing that allows to combine the different media (videos, images, text, etc.) in real time. For the arrangement of media, we utilize layers that define a z-ordering, as often seen in photo editing software. For each layer, it is possible to define a modulation color, the opacity and the blending mode. These parameters allow to fine-tune the compositing very well. In addition, the user can associate pixel shaders to each visual media object, which allows to define custom rendering effects.

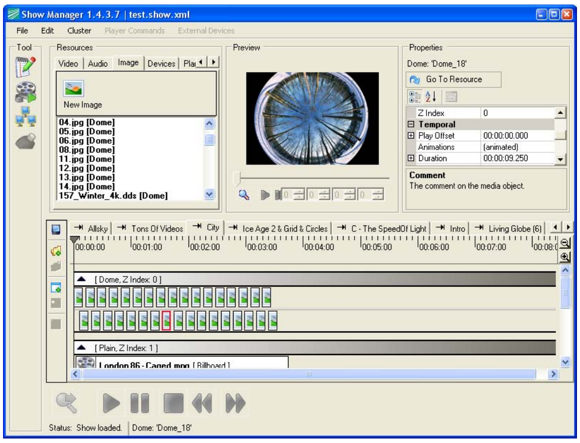

Figure 5: *Screenshot of the ShowManager showing its main window.*

Currently, the Player is capable of playing back 4k x 4k fulldome video content at 30 frames per second. It is not necessary to slice the video material in a pre-process. Instead, we use a specialized video codec capable of decoding only the part of the video that is actually rendered by the current PC. An example of this decoding is shown in figure 4.

Our system also supports the integration of external devices, such as lamps, spots, fog machines, or gobos. Currently, we implemented DMX, Midi and serial interfaces. In the show, a device is represented as regular object and can be edited and animated like any other media object.

4.2. The ShowManager

As illustrated in figure 2, our player reads shows from XML-files. These “shows” define the resources to be used, their spatial and temporal placement, animations, and the compositing. The ShowManager as a separate application lets users author shows very efficiently, but also allows to control the rendering cluster.

Figure 5 shows a screenshot of the main window of the ShowManager, which is split into two halves. On top it presents the resources of the show, a preview window, and allows the user to edit parameters of objects. Below, a timeline displays the media elements in the show. It allows the user to place new items by simply dragging resources onto the timeline. Additionally, existing items can be moved using drag-drop and changed in their duration by grasping the sides with the mouse. A “snap-to” mechanism aligns dragged objects with other objects in the show.

An advanced animation editor allows to edit keyframe-based animations. Different types of interpolation (linear, spline, etc.) can be selected. A graphical editor for the animation curves facilitates the direct manipulation of keys both in value and time.

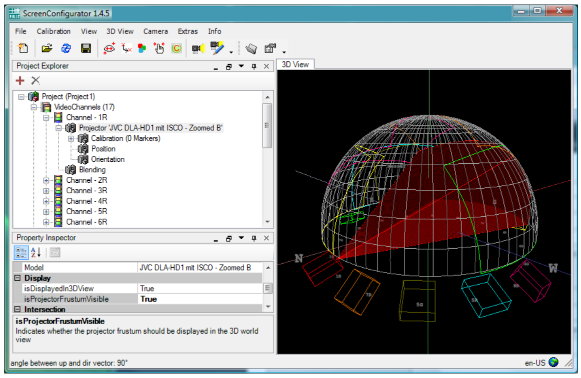

Figure 6: *Screenshot of the Configurator showing our dome setup.*

Besides allowing to author shows, the ShowManager simplifies the management of the rendering cluster. It can be started, stopped, and monitored directly from within the ShowManager. Additionally, shows can be uploaded and played-back, even in parallel to the authoring.

4.3. The Configurator

The Configurator is a tool for planing the physical setups of projection systems (see figure 6). It is used to define the shape of the screen (our system support arbitrary screen shapes), the number and types of projectors, and their positions and orientations. It has a 3D view that visualizes all these components including the light frustums of the projectors and the screen areas covered by their projections. With the Configurator, the user plans how the whole build-up will look like and can check everything, even before any hardware components are bought.

The soft-edge blending is calculated automatically using the whole overlapping areas between the projectors. All important information about the installation (including pixel sizes, the projection’s total brightness and resolution) are generated and written into a data sheet.

The Configurator contains multiple calibration methods for fast and easy projector fine-adjustment and color adaptation: manual, semi-manual and camera-based automatic geometry and color calibration (see sections 5.1 and 5.3 for details).

The Configurator writes out the following data files that are needed by the Player to execute the real time corrections: blend mask images to do the soft-edge blending, distortion meshes that define the warping for the geometric correction (including region-of-interest optimization data needed for efficient video-decoding of movie files with a resolution of 4k x 4k and beyond), and look-up tables for the color calibration.

5. Calibration

5.1. Geometric Calibration

The geometric calibration is done using the Configurator and is driven by a model-based approach. The user feeds parameters into the system, such as the dome diameter, the number of projectors and their positions. This input data is used to calculate a first geometric calibration — i.e. the needed distortion of the flat and rectangular (partial) projector images so that they are correctly adapted to the curved dome surface and produce one big projection. It is not important that these input parameters are chosen in perfect accuracy. No matter how much effort the user puts into exact measuring of these parameters, there will be (more or less) visible misalignments in the projected images at this step of the set-up. A flawless image will be assured later, after executing the calibration refinement processes we describe in the following.

The Configurator supports three kinds of geometric projector fine-adjustment: marker-based calibration, manual calibration, and camera-based automatic calibration.

As a first step, the user can choose to execute the marker-based calibration, starting with defining some marker positions on the screen. These are usually some points, corners or edges at the screen itself or some LEDs, laser beams or color markers that are only visible in UV light. The user then moves a cursor in the projected images to the marker positions on the screen. Using this information, the software calculates the intrinsic (field-of view, aspect ratio, off-axis angle, lens distortion) and extrinsic (position, orientation) parameters of the real projectors much more precisely than the user could measure them by hand. After this process, the projected partial images will match significant better than before.

Nevertheless, there still may be some visible geometric errors in some areas. To eliminate these, the user can select the manual projector calibration or the camera-based automatic projector calibration.

During the manual projector calibration, the user moves a cursor in the projector's image, selects areas in this image that seem to be misaligned and distorts them (e.g. move them upwards, to the right, etc.). The position, size and shape of the influenced area can be adjusted by parameters. The user executes such manipulations on different parts of the projector's image until all visible mismatches in the overlapping areas have disappeared.

During the camera-based automatic projector calibration, one or more cameras take a number of pictures while the projectors are displaying images with special stripe patterns generated with color-encoded structured light. The images are filtered and analyzed which lets the software recognize the errors in the projections because it has enough information about where the projectors' pixels are located on the screen and where they *should* intersect the screen geometry. The warping parameters for each projector are adapted so that the alignment errors are reversed and, thus, eliminated. The cameras are calibrated using the above mentioned markers once before the first automatic projector calibration is executed.

5.2. Blending and Brightness Correction

Multi-projector systems have to deal with the edges between the projector images when connecting the partial images of the single projectors in order to create the resulting total image. This is done using soft-edge blending. The brightness of each image area being part of the overlapping region in-between two projectors is reduced in a way that the resulting overlapping region is as bright as the rest of the global projection to achieve a homogenous and uniform projected image. This is done by cross-fading the light intensity in-between the projection fields. Multi-projector systems are usually using a linear blending function. In the Configurator, we use sinus-based function smoothing to avoid the sharp kinks at the start and the end of the blending areas. Finally, the blending function must be inverse-gamma corrected because of the non-linear brightness slope of common projectors.

The definition of the location and size of the blending region can be done manually, although this is a time-consuming task if good results are to be achieved. For this reason, the Configurator automatically calculates the optimal blending regions without any further user input, similar to the approach described in [BR05]. For each point in the overlapping region, the algorithm investigates how many projectors are covering this point. The influence in this point is weighted between the projectors: pixels near to a projector's edge get a smaller weight, while pixels near to an area where this projector is the only one that is projecting to get a higher weight. This results in blend images that smoothly fade out towards their edges, and in the sum the projection brightness is uniform.

Even without the usage of any measurement devices, the Configurator is doing a second kind of brightness correction in addition to the soft-edge blending. All pixels of each projector are corrected with resepect to their brightness that they have on the screen. Pixels that cover a relatively small area on the screen (and thus look brighter than other pixels) are darkened by the system relative to their size so that the whole screen gets a homogeneous brightness, even if the projectors have strongly different distances and angles to the screen or have different lenses and lamp powers. This correction is based only on the parameters the user has fed into the system. That means it cannot handle projector brightness irregularities like vignetting. This task is left to the color calibration algorithms described in the subsequent section.

An example of our geometric calibration and blending is shown in figure 7.

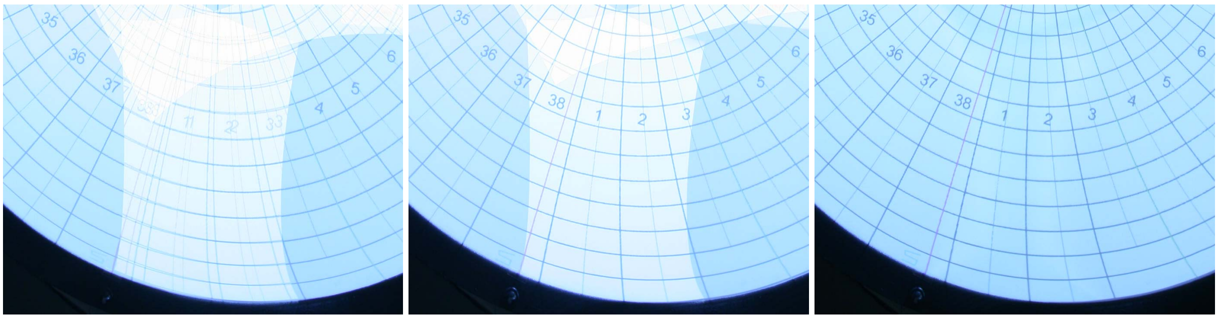

Figure 7: *Example of our camera-based automatic projector calibration and soft-edge blending. From left to right: Uncalibrated, calibrated, calibrated and blended.*

5.3. Color Calibration

Our color calibration is subdivided in two steps: *intra-projector calibration* to correct the non-spatial uniformity of the image once projected on the curved screen, and *inter-projector calibration* to correct the color differences between the different projectors.

5.3.1. Intra-projector calibration

The first operation investigates the spatial chromaticity variations over the illuminated surface of each projector. The variations originate from the projector lens distortion, and the age and type of the lamps (e.g ultra high pressure lamps). As a consequence, an originally uniform RGB level may appear non-uniform on the screen. The intra-projector calibration produces a 3D look-up table (LUT) per color channel: two dimensions for the pixel location and a third dimension for the pixel level. The LUT ensures to obtain a uniform level on the screen. The main disadvantage of this operation is that it might slightly decrease the maximum RGB level of a projector.

In order to compute a LUT for each projector of an installation, we repeatedly project and measure ramps of pure red (R), green (G) and blue (B). With these information we can measure the response curves (both global and by color channel) of a projector and determine its gamma value. Typically, projector response curves have a gamma shape: x .

One difficulty is to measure the non-uniformity in a color space corresponding to the human color perception. Ideally, the use of a camera giving CIE XYZ values directly should solve this problem. Such cameras with sensors presenting the same sensitivities as the the CIE 1931 standard observer exist but are very expensive. On the other hand, research in tiled displays with projectors has shown that this correction can be based only on the intensity measurement of the various ramp levels projected [MS04], while assuming negligible chromaticity variations. We verified this assumption by taking measurement of the projector primaries with an XYZ camera (see figure 8). These measurements correspond to various spatial locations on the screen surface of a dome installation with two projectors. We can observe a small color shift on the illuminated surface, which makes it possible to assume no spatial chromaticity variation. This assumption allows to use regular SLR camera as measurement device.

If a regular camera allows to take high resolution pictures (and then accurate spatial information), the direct use of the RGB values should be avoided, especially if the camera sensors remain unknown [VT93]. One possible approach is to take an high dynamic range (HDR) image [DM97] of each ramp level [PS07], from which we use only the luminance values. The advantage of this approach is the ability to work with a higher dynamic range of values for each pixel. In this usage of HDR images, we do not need to perform tone mapping since we use the camera as a measuring device.

Once we corrected the non-uniformity, we employ the following strategy for intra-projector color correction: if the intra-calibration process reduces enough differences between the projectors, there is no need for more correction (i.e. the color differences between the projector primaries are not perceivable). If this is not the case, additional gamut mapping has to be considered.

5.3.2. Inter-projector calibration

This operation requires to estimate the common gamut of the installation, i.e. to define the common displayable colors by the projectors [PS07, WCL03]. For this, the CIE XYZ primary values of each projector have to be measured with a spectrometer.

Once the common gamut is defined, the gamut mapping operation itself is performed by a matrix operation: for each projector, we need to compute the new RGB values which will project the same XYZ values. The great advantage of the gamut mapping operation is to ensure that color differences are not visible to the human eye. However, it can also drastically reduce the color dynamic. The following equation shows how the RGB values are modified before projection:

$$c' = g_p^{-1}(\mathbf{M_p}\mathbf{M_c}c\ ) \quad (1)$$

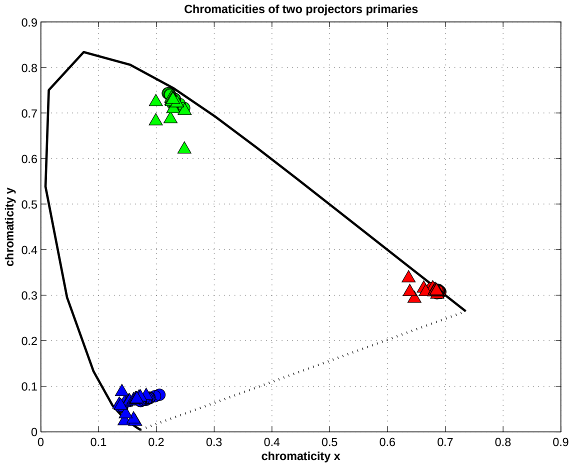

Figure 8: *Illustration of chromaticity variation between two projectors. The measurements were taken with a camera giving directly CIE XYZ values and describe various spatial locations over the dome projection surface.*

where $\mathbf{M_p}$ is the matrix of the projector primaries, $\mathbf{M_c}$ the matrix characterizing the common gamut, c the corresponding RGB values for the installation response curve (which is defined by the user) and $g_p^{-1}(c)$ the inverse response curve function of projector p.

In an optimal case the transformation in equation 1 involves the same matrix $\mathbf{M_c}$ for all projectors. In order to avoid loosing a too much color dynamic, however, we can compute a new $\mathbf{M_c}$ per projector by optimization. By doing so, a tolerance of color inaccuracy can be introduced without introducing perceivable color differences.

6. 3D Stereoscopic Dome Projection

On flat surfaces, the visualization of stereoscopic content has been readily available for many years. Different technologies have been developed, such as shutter glasses, or polarization filters. However, on dome surfaces, the realization of stereoscopic playout is much more challenging.

In planar and cylindrical displays we can assume that the viewers usually have a horizontal eye orientation to the projection surface and are looking straight to the screen. This makes it easy to create one view for the left eye and one for the right eye. In domes, it is different because particularly close to the zenith, the orientation of the left and right eye relative to the screen differs significantly among viewers at different positions and angles. For example, observers standing in the dome center and looking up to the zenith have a reversed eye orientation if they turn around 180 degrees, still looking upwards. This means that if the observers are free to choose their position and orientation there cannot be a reliable stereoscopic perception.

There are several options for stereoscopic display. First, the polarization filter stereo technology is a relative easy and low-price solution to execute the image separation for the stereoscopic effect. However, on a curved screen like a dome it is not possible to use this method because it needs a special paint (silver screen) that keeps the polarization of the projected light that is reflected from the screen surface. The high specular reflection characteristics of silver screens makes it impossible to achieve a homogeneous brightness distribution of the projection for all viewing angles. Second, the shutter glasses stereo technology needs expensive hardware. Projectors that run at least at 120 Hz and genlocked graphics cards are required for a smooth and comfortable viewing experience. Finally, the Infitec stereo technology uses comb filters (see also section 2) and does not have the disadvantages of the other methods. Thus, we decided to use Infitec filters for our 3D stereoscopic setup.

In general, the drawback of using 3D glasses is that they usually limit the human visual field significantly, which people may find uncomfortable. Currently, however, there are no stereo technologies available that work without glasses and that are suitable for large-scale curved screens.

The most challenging aspect of stereoscopic projection in a dome is content generation for the different viewing directions. We use two different modes:

- In the "global stereo mode", the view calculations for the two eyes are done from the static position in the dome center. The viewing direction of both eyes is optimized for the main direction of the dome. Hence, this method can be best used if the audience is seated at fixed positions. The disadvantage is that the optimal stereoscopic perception is only given in the main direction. In other directions, disparity and, thus, the the stereoscopic impression vanish. Full dome stereo movies are often created using this method.
- In the "local stereo mode", the view calculations depend on the displayed graphic objects. We can stereoscopically present images, movies or 3D objects on all position in the dome. However, this method is only feasible for objects with a size smaller than 90 degrees. Furthermore, it does not work properly for objects in the zenith. For these objects the rendering algorithms could be adapted so that the eye disparity is slowly decreased as the objects approach towards the zenith. Generally, the local stereo mode is particularly suitable if people move around freely in the dome and do not have a common viewing direction.

In our dome projection system, it is possible to use both modes. In fact, the two methods can even be displayed simultaneously if assigned to different layers in the show.

7. User Interaction

In the past, digital dome presentations have usually been non-interactive. The shows have been created and pre-rendered beforehand and were simply played-back, which does not allow any interaction with the audience. However, to enable more exciting experiences, support for user interaction is highly desirable.

Our dome projection system is a real time compositing system that renders the media on-the-fly during playout. This allows us to introduce different interaction schemes. We can manipulate any media in the show interactively and in real time utilizing our animation capabilities. All parameters that are animatable — such as opacity, position, size, etc. — can be modified within their ranges.

Our system also allows to process live video content, which is particularly interesting for telepresence or broadcasting scenarios. The live video can either cover the entire dome surface as a fulldome video. Alternatively, it is possible to map the the live stream onto a billboard and place it at different positions in the dome. Naturally, the animation parameters of the live video can also be manipulated interactively.

We implemented two different methods for integrating live video content. First, we can capture the video stream on each rendering client. The advantage is a very short delay. Second, we can setup a server that captures the video stream and distributes it to the clients via an UDP channel. Since the video server can usually be installed on one of the existing computers in the cluster, this method does not need any additional hardware for distributing the stream in the cluster.

Furthermore, we can define pixel shaders per object for advanced rendering effects. Employing a mechanism similar to the manipulation of show objects, the parameters of the pixel shaders can also be manipulated in real time.

8. Conclusion and Future Work

In this paper, we described the construction of our 3D stereoscopic dome and the software system for multi-projector playouts. As discussed, the small size of the dome implies several problems not present in larger installations that have to be handled. Furthermore, we presented several special features of our system, such as automatic geometric and color projector calibration, automatic soft-edge blending, real time media compositing, different stereoscopic rendering techniques, and user interaction.

In the future, we will increase the maximal resolution in the dome in order to further enhance the visual quality. Concerning the global stereoscopic rendering, we will research how to improve the stereoscopic impression outside the main viewing direction. Additionally, we want to investigate methods for directly editing and manipulate objects of a show. For this, we plan to evaluate different intuitive user interfaces, such as multitouch devices or gesture recognition.

As already mentioned, our live video streaming allows to use domes for telepresence and video conferencing systems. However, this requires wide-area network streaming with very high data rates. Another interesting application that could benefit of our interaction capabilities is multi-user gaming. Here, we want to develop novel schemes for group interaction in a dome. Finally, domes could also be used for evaluating simulation results and doing design reviews, for example in the automobile industry.

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