A Single Light-Source Uniform Tiled Display

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Abstract
We present how a single light source was used to drive multiple video projectors in a tiled display in order to achieve better tile-to-tile color and brightness uniformity. Additionally, a combined tiled-Fresnel and mask assembly was developed which further improved brightness uniformity and reduced color and brightness shading artifacts.

Introduction

High-resolution tiled displays (sometimes called "Power Walls" or "Video Walls") are often constructed by arranging multiple video projectors into a 2D matrix layout behind a rear-projection screen. The goal of this configuration is generally to produce a single seamless high-resolution output image. Unfortunately, variations in a number of optical, mechanical, and software components inherent in these types of projector-based tiled display systems work against this goal. Configuration differences and changes, which naturally take place over time in some components, lead to color and intensity differences across tiles.

While a number of difficulties in achieving seamless output exist, it is the color and brightness uniformity problems and solution approaches, which the High Density Display (HDD) project is attempting to address, and which this paper will primarily describe and explore.

1. Uniformity Problems

There are several challenges to producing a single seamless output image in a tiled display. For example, ensuring that the geometry of the system is properly configured is important. Adjusting the size, aspect ratio, orientation, and distortion of each tile image, and, taking care to precisely align and abut tile edges (or alternately applying edge blending) are some parameters that can be controlled to minimize visible tile-to-tile transitions [1][2][3]. Several tiled display systems solve some of these geometry issues by employing automatic vision-based correction techniques [4].

While good geometric configuration is an important factor which effects the overall seamless quality of a tiled display, a common complaint by display users and maintainers has been the problem of establishing and maintaining consistent brightness and color uniformity across tiles. Users are certainly not shy about commenting when they see color and brightness variations on tiled displays. But, even more vocal complaints have come from the technical experts who have to configure and maintain these systems. Chief among the complaints is the painful and time-consuming process needed to regularly recalibrate projectors to keep them reasonably matched.

In 2000, the San Diego Supercomputer Center (SDSC) in collaboration with JVC's Digital Image Technology Center began construction of a 12 mega-pixel 3x3 tiled display designed to address issues in color and brightness uniformity and reduce or eliminate the need to recalibrate the display system. The project identified and addressed the underlying causes of tile variations, instead of finding workarounds for the symptoms after-the-fact.

To identify and discuss causes of uniformity variation throughout a projector-based tiled display system, it is useful to have an understanding of a system and its components. Figure 1 shows the standard imaging components used for a single tile of the display. The figure shows an electronics package (a), which takes a video signal as input, and controls light-valve (b) modulation on its outputs. The electronics package also provides software-controllable calibration of its inputs and outputs. Further, the figure shows the stages of the optical pipeline starting from the lamp (c), through condensing and integrator lenses (d), then through the dichroic/color filters (e,f), then through the X-block and light-valve assembly (g) and finally takes a path through which all channels of the modulated light are combined and sent through the imaging optics (h) to expand the image (i) before it reaches the screen (j).

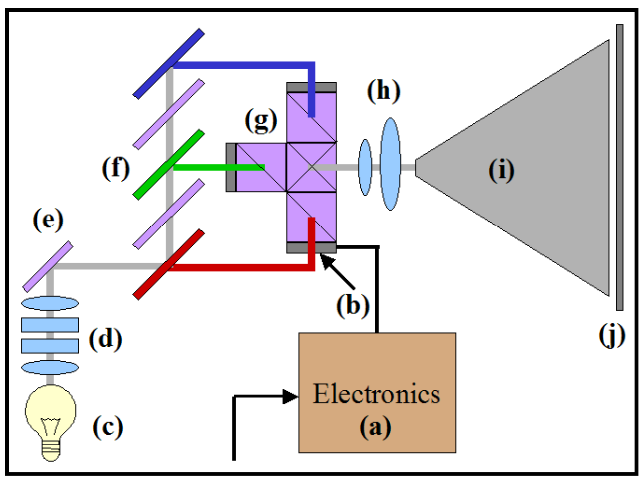

Figure 1: The standard projection pipeline.

By examining the characteristics of a single display pipeline starting from the lamp and progressing through the projector optics to the screen, we can begin to identify parameters that can lead to variability across tiles of the entire tiled display system.

1.1. Lamp Problems

Most projectors use some form of arc lamp as a light source (see Figure 2). An arc lamp is a gas-filled quartz vessel (a) containing two electrodes (b) between which a small plasma arc is produced (c) by applying a voltage. The type of gas used is often Xenon, Mercury, or some other gas that produces a complete spectrum of visible light.

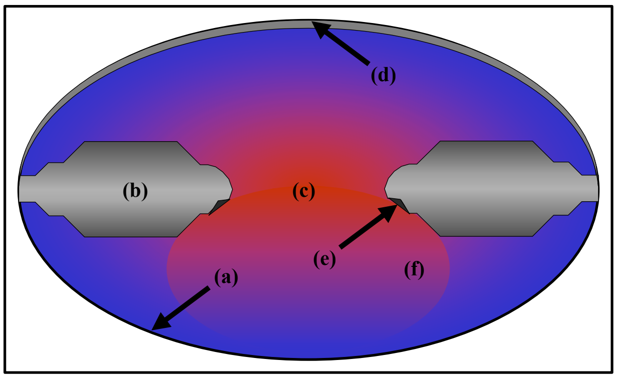

Figure 2: Arc-lamp.

While arc lamps provide reasonably consistent overall brightness over most of their lifespan, the shape of the arc may change over time as the electrodes decay (e) and metal and gas vapors deposit on the vessel walls (d). As the shape of the arc changes, light distribution across the light valve surface also changes to produce irregular shading variations. Though there is an expected central hot spot from the center of the arc and a drop-off to the outside, its the imperfect variations of the arc shape that produce less regular brightness changes that cause the output image to be more unevenly affected. Each lamp may also output different intensities along the color spectrum. Figure 3 shows the visible light output of our Xenon lamp measured with a spectroradiometer. The data has been normalized to show the overall amplitude differences across the visible spectrum. The peaks of the spectral envelope can vary, causing both color and intensity differences in the projected image. As all of these brightness and color changes occur over time in each individual projector, all projectors in a tiled display system may need to be recalibrated in order to achieve similar output levels across tiles.

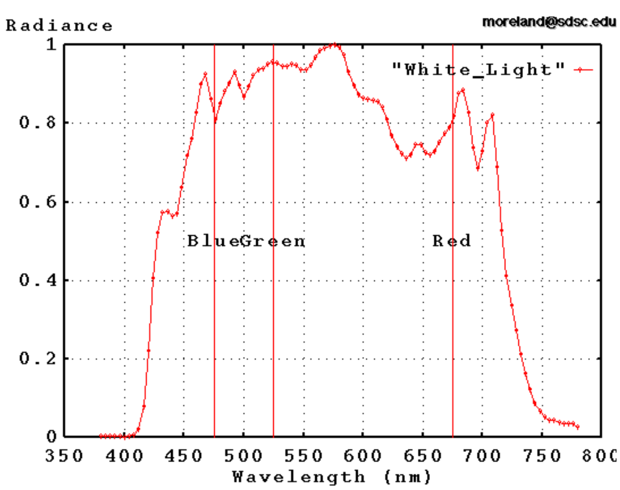

Figure 3: Lamp output.

1.2. Projector Problems

Projectors contain an electronics package that provides inputs for video sources and outputs that modulate one or more light valves. Most projectors provide some means of adjustment to configure how a video signal is processed and how the image is produced on the light valve. While most projectors provide basic control of overall brightness and contrast, there is a great deal of variability between projectors in the level of control provided for more advanced parameters such as video black-level, video set-up, color gammas, and shading. If these parameters are not adjusted with care, tiles will be poorly matched. These adjustments can take a technician countless hours to adjust and may have to be performed often.

There are a number of pre-imaging optics in a projector that can also alter the color and brightness of input light and ultimately the color and brightness of the image. A combination of dichroic filters and mirrors are used to split the incoming white light spectrum into red, green, and blue primary colors (Figure 1-e,f). As the color and brightness of the lamp light changes, the color and brightness coming from the dichroic optics also changes. Likewise, the dichroic coatings within an X-cube assembly (Figure 1-g) can pass slightly different intensities of light as the input light changes. As spectral intensities vary from the lamp through the dichroic optics, the relative intensities of primary colors shift as light is shunted from one filter to another (very much like passing a varying signal through a series of low-pass and high-pass filters in an electronic circuit). Recalibration may again be necessary.

As light travels from the pre-imaging optics into the light valves, it is focused and shaped into a rectangle using a series of integrator and condenser lenses (Figure 1-d). This process maximizes the amount of light focused onto the light valve’s imaging surface and provides an opportunity to blend the light into a more uniform field. However, to avoid color-fringing artifacts and intensity roll-off at the edges of the active imaging area of the light valve, the rectangular light field is usually aimed and focused to overshoot past the edges of the active imaging region of the light valve (see Figure 4). The side effect is that “junk” light from around the borders of the light valve is transmitted to the screen as a gray hazy frame around the image. While the junk light from a projector does not affect the image for the corresponding tile, the border of junk light is overlaid over the edges of all neighboring tiles, “muddying” the all of the image borders of each tile.

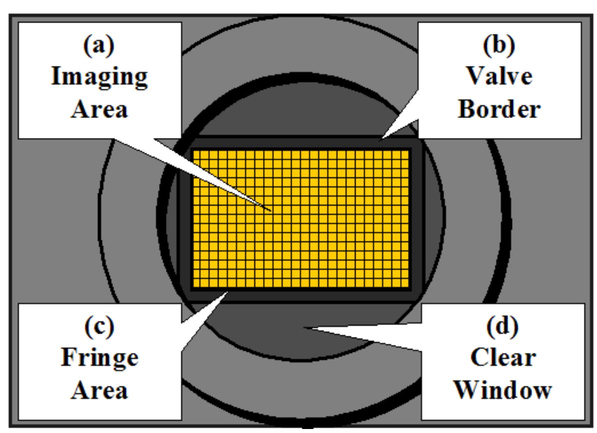

Figure 4: Light Valve

Whether a projector uses transmissive or reflective light valves, when pixel elements in the light valves are turned off (so that the resulting image pixels should be off), some light still escapes past the light valve and is transmitted through the imaging optics to the screen. This off-state light leakage causes image areas that should be black to appear dark gray.

As modulated light from each light valve travels through the X-cube assembly to the imaging optics (Figure 1-h), the image is expanded from the size at which it is produced on the light valve (often < 0.9 inch diagonal) up to the final projected size when it hits the screen (often multiple feet on the diagonal). Since the projected image forms a diverging pyramid of light, if the image is viewed off-center the image field looks brighter on the side closest to the viewer. Those light rays are directed toward the viewer, whereas the side of the image furthest away from the viewer is darker because those light rays are directed away from the viewer. When projected images are placed side-by-side and viewed off-axis, a saw-tooth of light-dark-light-dark transitions are prominent at the tile boundaries.

1.3. Screen Problems

Many rear projection screens provide some amount of light diffusion. In part, this enables light to be scattered enough that the image can be seen from multiple viewing angles, but not so much that the image is blurred beyond acceptable levels. However, the same screen properties that provide beneficial diffusion can also cause color-shading artifacts. Often, very fine clear beads of material are embedded in one layer of the display surface to provide diffusion. But, the beads also act as very small lenses or prisms that can scatter or refract varying wavelengths of light in different directions. Figure 5 illustrates how light hitting a spherical bead at oblique angles produces a path and refraction pattern similar to that of a prism.

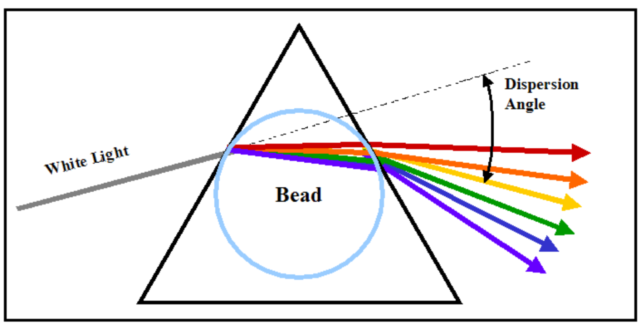

Figure 5: Refraction off of a diffusive bead can act like a prism.

As the projected expanding light hits the screen, the central portions of the imaged light hit perpendicular to the screen, whereas off-axis light hits the screen at sharper angles out to the edges of the image. Particularly as displays are built smaller using lenses with shorter throw distances, the angles of projected light are more drastic and this prism effect can cause more color shading artifacts.

Each of the problems with lamps, projectors and screen creates color and brightness artifacts that make tiles different, edges evident, and destroy the illusion of a large seamless image.

2. Previous Work

Those organizations that have had the privilege to build, configure, and use tiled displays have also had the misfortune of having to commit time and effort to tuning, calibrating, and recalibrating projectors. It is this nuisance that the community loathes to repeat and which drives it forward to find a better way.

There have been a number of excellent studies that have analyzed the problems and challenges in trying to match color and intensity levels of multiple projectors. Careful examination of the each component in the system has lead to a number of clever and effective solutions for the software-controlled automation of projector configuration [1]. Computer vision techniques and render-time corrections in the rendering engine's frame-buffer have provided additional automatic color and brightness compensation [2]. Carefully measuring and characterizing projector color input responses and tuning outputs within a well-constrained common gamut is also useful to help solve the problem as well as to better understand the limitations of the projects themselves [3]. Techniques have also been developed to dynamically analyze and control color, intensity, and geometry configurations when projectors overlap [4].

3. Uniformity Solution Approach

While the use of high-resolution cameras, light sensors, compute resources, graphics hardware, and custom software can be applied to alleviate many symptoms of the projector-matching problem, this project has set out to identify and alleviate a number of the underlying causes of those problems.

In this project, we built a 3x3 tiled display containing 9 JVC G-1000 video projectors with D-ILA (Digital Image Light Amplifier) light valves. Each tile runs at 1280x1024 pixels (almost 12 million pixels total). We used a Photo Research PR-650 spectroradiometer and several light meters to take our measurements. Ten Linux PCs were used to drive the display with NVidea GeForce-2 graphics cards.

The components that we have integrated in order to address the causes of uniformity problems have many interactions with one another. To simplify the discussion, we'll introduce the overall design of the improved system here and later go on to discuss the individual elements and how they each function, interact, and improve system uniformity.

Figure 6 shows the modified display pipeline of our system. Two projector modules are pictured to illustrate how components are shared though 9 modules exist in our current implementation. The figure includes the same electronics packages (a) and light-valves (b) as in Figure 1. But, in Figure 6 our modified pipeline starts with a shared lamp (c) and continues through shared condensing lenses (d). The new pipeline does not pass through integrator/condenser optics as before, but instead through an extended set of shared dichroic/color filters (e). Light then passes from each of the red/green/blue light channels into our fiber-optic distribution cables (f, see also Figure 9). From the outputs of the fiber-optic cables, the light is passed through integrator/condenser assemblies for each color channel (g). The path through the prisms, light-valves, and X-block (h) and the imaging optics (i) is the same as before. But, just before the image reaches the screen (m), a masking mechanism (k) crops out the junk light (k), and the remaining useful image passes through the tiled Fresnel lenses (l).

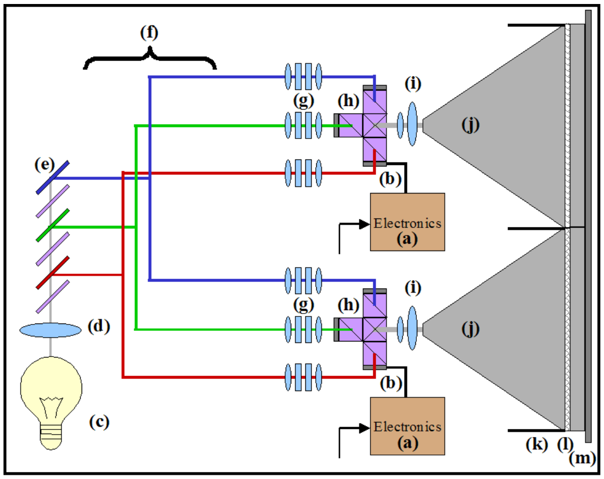

Figure 6: Our modified projection pipeline.

3.1. Lamp Solution Approaches

The projector lamp is the component that varies more than any other over time. It has a major effect on output uniformity across tiles. Because each projector has its own light source, the variability between projectors can be exaggerated as color and brightness shift in opposite directions between projectors.

As the lamp arc changes intensity and color over time, what started out as calibrated projectors now become uncalibrated in relation to other projectors. Figure 7 shows our single Xenon light source as well as our additional shared dichroic filters. This shared light source enables the system to tolerate brightness and some color variations because all projectors track together with the changing single light source. That is, as the light decreases, all projectors dim together. As the lamp ages, all projectors experience identical color shifts.

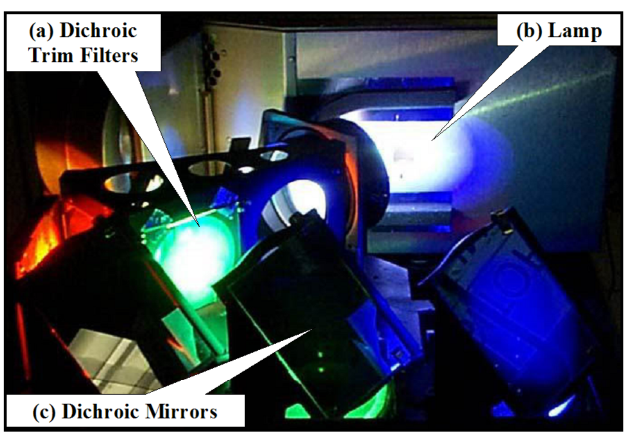

Figure 7: Common light source and dichroic trim filters.

Figure 8 illustrates how the addition of extra dichroic trim filters narrow the common light spectrum enough that variations in the remaining projector dichroics are minimized. That is, we can pre-compensate for variations of some of the optics (ie: the X-cube) before the light reaches the projectors downstream in the optics pipeline.

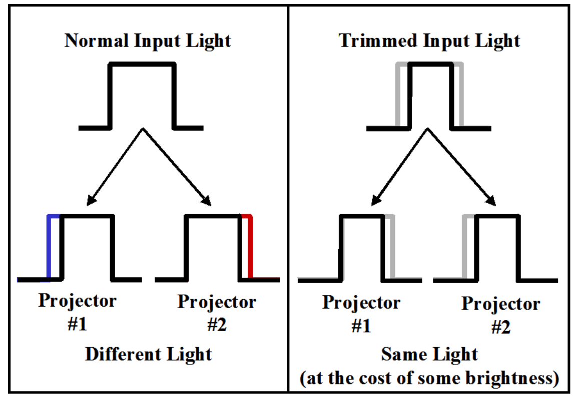

Figure 8: Common light trim for projector matching **.**

In order transmit the light from the shared light source to each projector, flexible quartz fiber-optic cables run from the shared light source to each projector. Three cables are used, one for each primary color (red, green, and blue). Each cable is composed of thousands of smaller individual fibers that are randomly distributed within the cable to provide even light distribution. Each of the 3 cable bundles then split into 9 smaller fiber bundles (one sub-bundle for each projector). Adjustable fixtures enable light from the light source to be focused into each of the three fiber bundles. Figure 9 shows one of our original “3-way” fibers (again, the production system uses 9-way fibers).

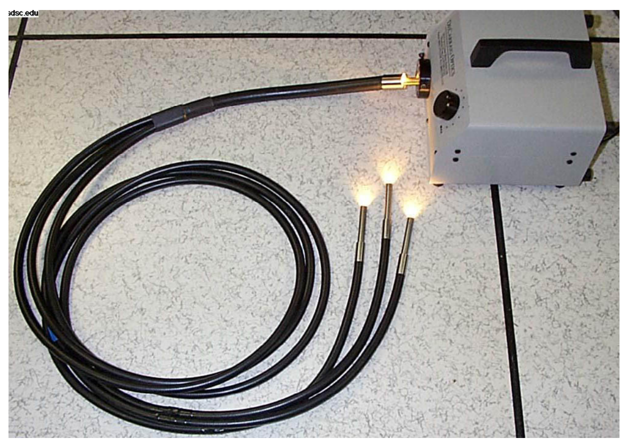

Figure 9: Fiber-optic distribution cables/splitters.

3.2. Projector Solution Approaches

As the lamp arc changes shape and color over time, light distribution across the light valve surface also causes irregular variations in the image. Figure 10 shows our adjustable fixture that receives and holds the light input fiber. It also contains the per-color-channel integrator/condenser lenses. Following any of the 3 panels (a, b, or c) of the figure from left to right, the fixture routes the small spot of light from the fiber into a lens which increases the area. The light is then "chopped" into a grid of rectangular regions of light and is then "crossed over" and blended left-with right and top with bottom. The result is that most of the fall-off in one region of the light field is blended with the opposite regions in order to effectively cancel out spatial variations. The lens stack is similar to that used in the original projector, but our system has a separate stack per color channel so that each input can be shaped, aimed, and focused independently.

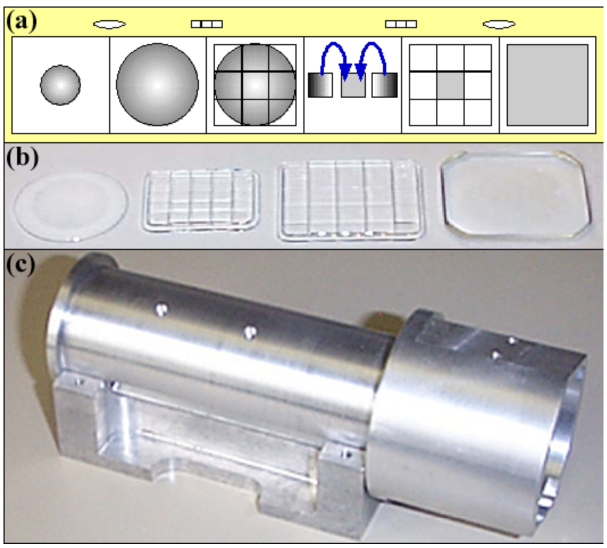

Figure 10: Fiber input and integrator/condenser lens assembly.

Calibration of each projector's electronics configuration still plays an important roll in achieving uniform tiles. But, because the electronic settings remain stable over time and because lamp aging issues have been minimized in prior stages of the pipeline, the projector calibration process does not have to be repeated as the lamp changes. Nevertheless, making careful adjustments to each projector is vital to achieving a good uniformity.

We have found that adjusting set-up and video levels (or black and white levels) to maximize the contrast ratio, and matching the outer limits of those parameters across all projectors is the most important step to get right. If this is not done well, tuning gamma tables and shading parameters correctly will not be possible. Furthermore, getting the darkest blacks possible during the calibration process will minimize the visible effects of off-state leakage from the light valves.

3.3. Screen Solution Approaches

Three different problems that deter tiled display uniformity are caused directly by the fact that projectors emit a diverging volume (pyramid) of light. These problems are:

1) The off-axis viewing saw tooth affect.

2) An overall reduction of observed brightness because light is not directed or concentrated outward (perpendicular) from the screen.

3) Color refraction (prism-like) shading artifacts when oblique light rays interact with the diffusive elements of the screen.

By adding a Fresnel lens with the appropriate focal distance between each projector and the screen, all three of the angle-induced problems can be completely eliminated. Figure 11 shows the combined Fresnel and masking system we have developed.

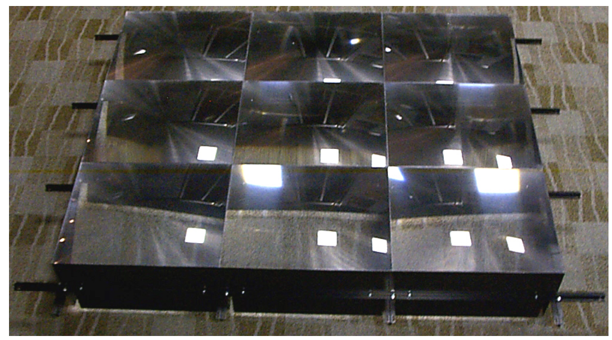

Figure 11: Tiled Fresnel and junk-light mask system.

A mask was designed to be an integral part of the Fresnel assembly: the mask "blades" also act as the mounting framework for the lenses. Notice also that the "blades" of the mask are large and are mounted parallel to the light and perpendicular to the lenses. While early mask designs entailed the use of very precisely sized and positioned strips mounted perpendicular to the incoming light, we found that the blade approach we developed enables the mask material to be cut and mounted with less accuracy but with better overall effect. As the pyramid of light diverges as it reaches the screen, the outer junk-light border is absorbed across a wide swath of each blade as it approaches the screen. The portion of a masking blade closest to the projector can, in fact, be bent several inches or badly warped and will not interfere with the active area of the projected image (see Figure 6-k).

More importantly, the addition of the mask removes all of the unwanted junk light before it reaches the screen. This eliminates the brightened-borders that would normally be present at and around the seams of each tile.

4. Results

Figure 12 shows output from the display.

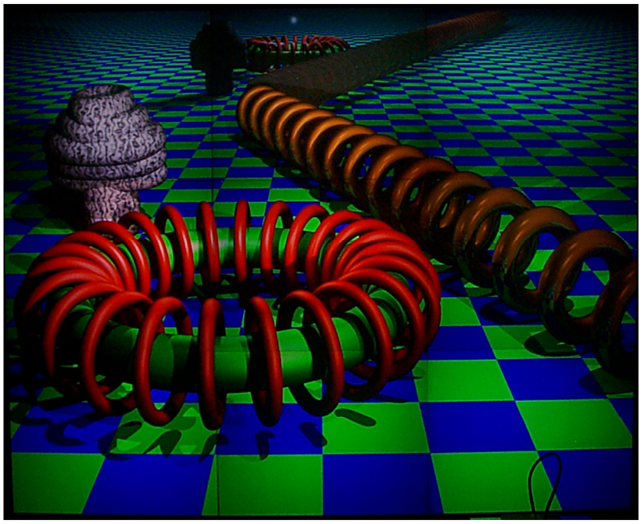

Figure 12: Output from the display.

A spectroradiometer was used to sample light measured from the front of the projection screen with a white field as input. The figure below shows a very good intensity and spectral correspondence in the blue outputs (left peaks). The red outputs (right peaks) show intensity variations primarily in the high wavelengths. The green outputs show spectral variation on both the high and low ends of the spectrum due to the frequency range limits of our off-the-shelf dichroic filters. We anticipate achieving even better matching given more carefully selected filters.

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5. Conclusions

Through the use of a common light source and fiber-optic distribution, we improved color and brightness uniformity between projectors and reduced the need to recalibrate projectors. By adding dichroic filters to trim colors narrower than any one projector's optics effect, we improved color matching out the lens across all projectors. Per-color channel integrator/condenser lenses enable more control over shaping and averaging out shading problems across the light valves. The tiled Fresnel lenses completely eliminated the off-axis viewing saw-tooth problem, improved the overall brightness, and reduced prism/refraction artifacts at the screen. Finally, the integrated mask system removed all of the junk light at the borders of each tile, thus removing the "halo" around each tile image.

It may be argued that, someday a single tile-less high-resolution display technology will be produced (perhaps large flat-panels, OLEDs, laser-based systems, etc) which would do away with the need for tiled displays. Thus, the uniformity problems caused by tiling discrete displays together would be a passing problem. However, there are undeniable performance advantages in driving discrete tiles in a tiled display using parallel graphics engines. And, users will probably always want higher resolutions. It is therefore our belief that, although the resolution of individual displays may increase, the desire to tile them together and leverage parallel rendering will continue. The need to address seamless tiling challenges will probably continue.

6. Future Directions

We have already begun early discussions on how to improve the system even further. We believe that we have a new shared light source and projector configuration which could vastly simplify the changes necessary to each projector. This could make the common light source technique available to just about any projector-based tiled display system. We also have been discussing the use of alternate light sources (perhaps lasers) in order to increase contrast from 800:1 up to something approaching 3000:1. We've also been approached to consider upgrading each projector from 1280x1024 to 2048x1536 (resulting in over 28 million pixels in a 3x3 tile configuration)

Acknowledgements

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