3.2: High Dynamic Range Projection Systems

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Abstract

Digital cinema and home theatre applications need to compete with analog film in terms of image quality. The single most important performance specification of a projection system, and the largest gap in the competition between digital and analog projectors, is the relatively low dynamic range of luminance of current digital projectors. In this paper we introduce a novel digital system capable of displaying images with a high enough dynamic range to rival analog film. The projection system described is based on a serial combination of light modulating devices, such as two liquid crystal micro-display panels within a projection light engine. One of the modulation steps can be of lower spatial resolution and contrast. This increases the optical efficiency of the system and avoids optical artifacts. We describe several hardware implementations of this approach as well as the required image processing. Finally, we present an evaluation of the designs in terms of performance, image quality and cost.

1. Introduction

Recent years have seen a rapid expansion in the digital projection market. The growing demand for home theatre installations and digital cinema facilities has driven significant innovation in the projection space in both spatial resolution and contrast. Rear-projection television (TV) sets have lost market shares to flat panel TVs due to their mediocre image quality, frequent lamp failure and bulky design. Improvements in image quality, a trend towards light emitting diode (LED) based light engines and new optical designs enabling an overall display thickness of as little as 6.5 inches are resuscitating the market. The most cost-effective and simplest size-scaling technology that enables large images is projection. Almost all movie theaters use projection systems and the TV market for sets larger than 50” is still dominated by rear-projection technology.

The contrast ratio of consumer displays is commonly specified as the ratio of luminance resulting from a full-on and a full-off screen signal. Transmissive micro-display technology features contrast ratios of 600:1 or more while digital micro mirror devices (DMD) can already operate between 1,000:1 and 2,000:1. Emerging liquid crystal on silicon (LCoS) projectors continue to push the envelope with contrast ratios of up to 20,000:1.

Current digital projection of any kind remains limited to, at best, three orders of magnitude of simultaneous contrast. On the other hand, analog film offers approximately four orders of magnitude. The real world around us often exceeds five or even six orders. Related to this limit is the relatively low peak luminance level of projectors. The low contrast of the projection system prevents higher light output because black levels would otherwise be objectionably high.

There has been a recent trend in home theater projectors towards the utilization of a motorized iris that can dynamically control the global luminance depending on the video content. This has successfully addressed dimming problems associated with light sources such as ultra high pressure mercury discharge lamps (UHP lamps) and boosts the on-off contrast significantly beyond the native panel contrast.

The ultimate standard in display image quality is the comparison of display performance against reality with respect to the capabilities of the human visual system (HVS). Simultaneous contrast is therefore a more meaningful measure of system performance, partially due to the fact that there are very few full black and full white scenes in the real world. A very robust alternative to specify the delivered range of visible luminance is the number of distinguishable grays (NDG), which simultaneously accounts for the effects of brightness, contrast, ambient lighting, and quantization.

In this paper, we present a solution to the dynamic range limitation of projectors, which is applicable to all common projection light modulators (transmissive LCD, LCoS and DMD). We will discuss the optical design and related software of each implementation.

2. Limitations and Capabilities of the Eye

Real world scenes can contain luminance levels in the range of up to 14 orders of magnitude. The human visual system is capable of perceiving luminance levels in the range of about ten orders of magnitude. Within this range, the eye will adapt and can observe about five orders of magnitude of luminance simultaneously.

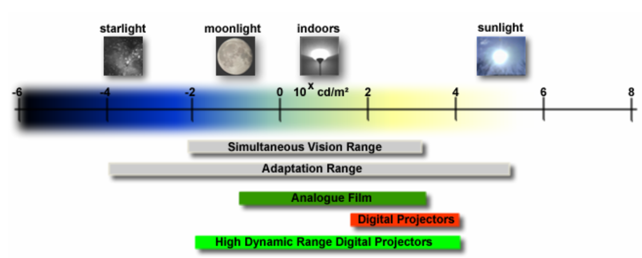

Figure 1: Logarithmic luminance scale; perception capability of the HVS and performance of different projectors

While analog film can capture around four orders of magnitude of dynamic range, most digital displays are only capable of producing images with a dynamic range as low as two to three orders of magnitude. The common approach to display data with a high dynamic range on digital displays is tone-mapping, which is a method to compress the luminance range of an image to better match that of the display. While these techniques somewhat improve the image quality of dynamic range constraint systems,

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there remains a significant perceptual gap between conventional projection systems and the real world luminance range.

Certain limitations and peculiarities of the HVS should be considered when designing a display system that more closely matches human perception capabilities. When light directly stimulates part of the retina, receptors near that part (up to about one degree) will also adapt to the same light level, even when not directly stimulated. This effect applies mainly to the central field of view (FOV). Imperfections in the media of the eye causes light to scatter within the eye and form a veiling luminance on the retina. This veiling luminance reduces the ability to perceive local contrast. In addition, lighting in the peripheral FOV can noticeably reduce contrast in the area of focus.

While the HVS can resolve differences in luminance at high spatial frequencies, its capabilities to differentiate between red-green and yellow-blue chrominance decrease as spatial frequency increases. The human contrast sensitivity of luminance is highest at around five cycles per degree and falls off as the spatial frequency increases further (i.e. the ratio of the maximum visible range of intensities to the minimum discernible peak-to-peak intensity variation decreases). The maximum red-green sensitivity is approximately one third of the maximum luminance sensitivity, while the yellow-blue sensitivity is even lower at approximately a sixth of the maximum luminance sensitivity. Above around ten cycles per degree, the HVS is hardly able to distinguish between red-green and blue-yellow.

3. Basic Projector Design

High dynamic range (HDR) projection systems place two image modulators in series and effectively optically multiply two images. The dynamic range of the final image is therefore the product of the contrast of the two modulators. This is very similar concept to a dual modulation direct view display [Seetzen 2003], which uses a conventional high resolution color modulator combined with a low resolution array of light sources which serves as the second modulator.

A direct transfer of this principle to projection is currently not practical due to the limits on miniaturization of small high power light source arrays. As LED performance increases further, it will be possible to manufacture a high density, high power LED array that can be used in a dual modulation projection system to increase the dynamic range. Today, it is easier to achieve the same effect by combining two non-emissive modulators in front of a bright light source. This fundamental principle of an HDR projection system is independent of the light engine choice.

A normal projection system uses a light source followed by appropriate optics to guide the emitted light onto a transmissive or reflective image modulator. The modulator adjusts the intensity of light of each image pixel. The modulated light is then sent through projection lenses onto a screen. The dynamic range of such a conventional system is given by the modulation range of the image modulator and some degree of additional reduction due to light scattering in the optics of the light engine.

The HDR projector augments the conventional light engine with a second image modulator. The light from the lamp is now modulated by both the original and the secondary image modulator. If the contrast ratios of the original and secondary modulator are c_1 and c_2, respectively, then the effective dynamic range of the output image will be $c_1 * c_2$. Because of the unique image processing required in a dual modulator design with different spatial resolution among the modulators, the full dynamic range of $c_1 * c_2$ is not always available for some images. This limitation and related solutions are explained in section 5.

The HDR projection system can be designed with a variety of components. The two modulators can be LCD panels, LCoS panels, DMD or most combinations thereof. Other less common solutions, such as schlieren optics-based modulators and electronic paper reflectors, are also possible. Independent of the combination, one of the modulation stages can be of low resolution to increase the optical efficiency of the system.

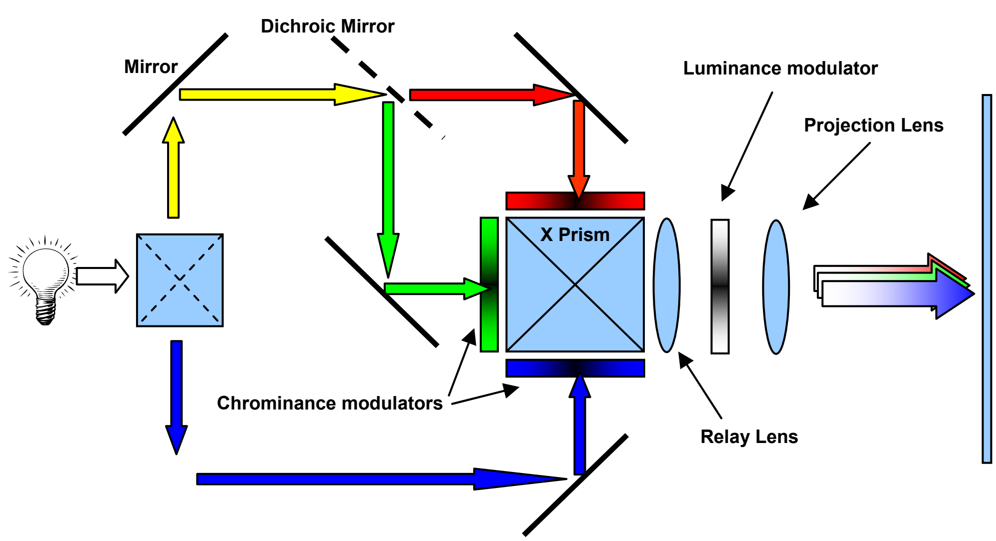

Figure 2: Example implementation of a three LCD projector augmented with a relay lens and a secondary LCD to modulate luminance

The benefit of a lower resolution in one of the modulation steps is two-fold. First, the optical efficiency of a modulator is directly related to the ratio of the active area of the modulator to the total area (the fill factor). Most modulators contain inactive areas as a result of control electronic components, lines between pixels, and other such light blocking elements. Since the control components necessary to drive a single pixel are approximately independent of the pixel size, the fill factor of a low resolution device is much larger than that of a high resolution device of the same physical size.

In addition, the image of the lower resolution modulator is optically blurred by introducing a physical offset to the modulator at the focal plane of the projection lens system. The resolution mismatch between the two modulation stages in combination with the slight blurring of the low resolution modulator removes any disturbing visual artifacts such as moiré patterns. These would be found in a dual modulation arrangement of equal resolution unless the two modulators were perfectly aligned at the sub-pixel level.

Clearly, even with the above efficiency improvements, some modulator combinations are more advantageous than others. In the following section, we describe different configurations and briefly discuss their advantages and limitations.

4. Implementation Variants

There are two fundamentally different variants to the implementation of dual modulation to increase dynamic range in projectors. Each makes use of unique characteristics of the HVS as described in section 2. In both designs, the dynamic range of the system is equal to the product of the dynamic ranges of the first and the second stages of modulation and the optical efficiency is linearly dependent on the efficiencies of the two modulation steps.

The first approach uses current high resolution projector designs which are modified to include an additional luminance modulator. This modulator can be of very low resolution, thus hardly reducing system efficiency (e.g. as few as 1000 pixels for a 1080p projector). A modulator of this kind would have to be customized, but can have a fill factor close to 99%. It can be placed before or after the recombination of the three high resolution modulators for the each of red, green and the blue channels.

The second approach inverts this concept to create a cost-effective variant: a low resolution chrominance modulator consisting of three panels that is enhanced by the addition of a single high resolution luminance modulation. The pixel ratio of the first to the second stage of modulation is small (i.e. 1:1.5 to 1:2.7) because the design makes use of the relatively low contrast sensitivity of the eye to chrominance and the higher sensitivity to luminance. A high resolution projector can now be built with three low resolution panels (e.g. 480p or 720p) for color modulation and a single high resolution panel (e.g. 1080p) for additional luminance modulation. Aligning three fairly low resolution chrominance panels can be significantly less costly in production and more robust throughout the life cycle of a projector.

In both designs, the resulting dynamic range, the amplitude resolution, and the combined optical panel efficiency of the complete system are approximately the product of the corresponding properties of the low and the high resolution stage modulators.

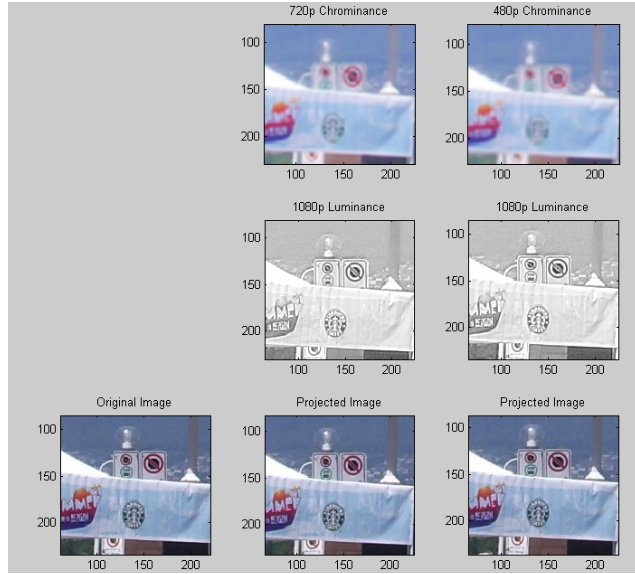

Figure 3: Sub-section of the simulation of a projector with a single 1080p luminance and three 720p (center) or 420p (right) chrominance panels

For either design, a variety of combinations of different modulators for chrominance and luminance is possible. In most designs, the first and the second stage of modulation need to be coupled with an optical relay lens system. Examples include a combination of a normal transmissive three-LCD projection system with an additional LCD panel. Likewise, a combination of LCoS panels can be used to achieve either of the designs above.

Instead of using a single additional modulator, it is possible to couple three low resolution transmissive LCD panels with three high resolution LCD panels. This design enables very pure color reproduction. The low resolution panels can be placed directly next to their corresponding high resolution panel which eliminates the need for additional optics. The amount of introduced blur can be controlled by adjusting the distance between each pair of panels. The low resolution panels can be driven either in parallel or separately controlled.

Another exception uses binary driven modulators such as DMDs or digital LCoS imagers which both lack the ability to adjust the amplitude of each pixel. Light from such a pixel is either “on” (light leaving the projector towards the screen) or “off” (light going into an absorbing cavity inside the light engine). Rapid switching between these two states generates the grayscale of the projection system due to temporal integration in the viewer’s eye.

Combining two frequency modulation based devices in series does not yield the dual modulation effect described above. If the two modulators are in phase, then they act effectively as a single modulator. If they are out of phase, then no light is transmitted at all. Either way, no gain in dynamic range is achieved.

Sophisticated drive schemes and coupling of such digital modulators can overcome these issues and allow dual modulation even with two stages of digital modulation. Another alternative is the coupling of a digital modulator with an amplitude modulating component such as an LCD or analog LCoS. Overall, the DMD/LCoS or DMD/LCD hybrid design is probably the least desirable of the combinations due to the necessity of adding a polarizing component to a non-polarized system. While a good choice of hybrid components can achieve acceptable efficiencies, the differences in the drive techniques of the two modulator types will add unnecessary complexity to the design.

5. Image Processing Software

The image processing software required to drive dual modulation displays is very similar for all implementations. In each case, the software needs to consider two image modulators with different spatial resolutions and color capabilities. The software also needs to compensate for the optical blur of the low resolution modulator. The degree of blur can be measured and characterized by a point spread function (PSF) for each low resolution pixel which is then expressed in corresponding pixels of the higher resolution modulator. This PSF is one of the core parameter of the image processing software together with the response curves and spatial resolution of the two modulators. These values will vary for the different design implementations but the remainder of the software implementation is design independent.

The luminance of the desired output image is distributed between the luminance and the chrominance modulators by applying a square root function, resulting in the drive values for the low resolution display. Given theses values and the parameters mentioned above, the optical blur can be precisely simulated at high resolution. A division of the desired output image by this blurred image will result in the necessary compensation mask that will be displayed on the high resolution modulator. In a closed-loop feedback, the compensation image is analyzed for saturated regions in which the corresponding drive values on the low resolution panel will then be locally enhanced to deliver enough light. Figure 4 shows the processing steps for this algorithm.

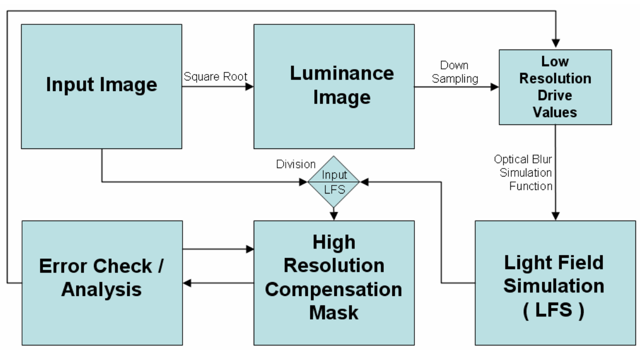

Figure 4: Main Image Processing Steps

A careful hardware design in combination with precise modeling of the PSF of the low resolution luminance modulator ensures that artifacts are always smaller than the veiling luminance introduced by scatter and adaptation in the HVS.

In a system with a higher resolution luminance modulator, the pixel ratio of the luminance to the chrominance modulator needs to be chosen while keeping the viewing environment in mind. Artifacts that cannot be accounted for are, at worst, marginally visible and only appear at boundaries between fully saturated regions at high spatial frequencies.

6. Results

A prototype unit has been built to prove the concept of both variants described above. A dramatic expansion of the dynamic range through serial combination of light modulators of different spatial resolution was demonstrated. The prototype is based on a typical projector that utilizes three transmissive LCD panels. In order to simulate both variants, a set of two panels per color channel were driven in concert (i.e. a corresponding second modulator for each of the three transmissive panels).

Figure 5: Photos of images on an ordinary projector (left) and the HDR projector (right)

The simultaneous contrast ratio was improved by more than an order of magnitude over that of the original projector. The resulting simultaneous contrast matched the theoretical product of the low (18:1) and the high resolution modulator (155:1) within a 5% range for a total simultaneous contrast of 2695:1. The focus of this study was the simulation of different possible setups. By driving the panels of the first and the second stage of modulation at different resolutions and controlling them either in parallel (simulation of a luminance panel) or separately (simulation of chrominance panels), we were able to show that discrete engineering of both concepts promises extraordinary results. The system is driven by robust video algorithms that include calibration and modeling features.

7. Impact

High dynamic range projection systems based on the designs described in this paper can deliver a dynamic range exceeding that of analog film projectors. The cost of such projection systems can be below that of conventional projectors if the lower resolution chrominance variant is used. Converting a movie theater from analog to digital can then be accompanied by an increase in simultaneous contrast performance rather than a decrease. Contrast ratios in home theater installations and rear-projection TV sets can be improved so that the technology is a more attractive alternative to flat panel and CRT TV sets.

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