A High-Dynamic Range Projection System

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ABSTRACT

The dynamic range in many real-world environments surpasses the capabilities of traditional display technologies by several orders of magnitude. Recently, a novel display capable of displaying images with a dynamic range much closer to real world situations has been demonstrated. This was achieved through a spatially modulated backlight behind an LCD panel. Combined with the modulating power of the LCD panel itself, this enabled the display of much higher contrast compared to an LCD panel with a spatially uniform backlight.

In this paper, we describe a further development of the technology, namely a high dynamic range projection system. This makes such display systems more widely applicable as any surface can be used for the display of high dynamic range images.

Our new system is designed as an external attachment to a regular DLP™-based projector, which allows the use of unmodified projectors. It works by adapting the projected image via a set of lenses to form a small image. This small image is then modulated via an LCD panel and the result is projected via another lens system onto a larger screen, as in traditional projection scenarios. The double modulation, by the projector and the LCD panel together, creates a high dynamic range image and an ANSI contrast of over 700:1.

Finally, we discuss the advantages and disadvantages of our design relative to other high and low dynamic range display technologies and its potential applications.

Keywords: High dynamic range, Display systems, Computer projection, Hardware

1 INTRODUCTION

1.1 HDR Background

In the past few years, the issue of limited dynamic range of both imaging devices and displays has been extensively studied in the computer graphics community. In addition to being able to produce such imagery via methods such as physically based rendering [8], algorithms have been developed for capturing both still images [1, 6, 7, 9] and videos [4] of real environments with extended dynamic range.

As the dynamic range of luminance of real and synthetic images often exceeds the capacity of current displays by orders of magnitude, new approaches to enable their presentation were also developed. One of the ways to display high dynamic range images is to transform the original range of intensities into a significantly smaller range of intensities a common desktop monitor can reproduce. This process is called tone mapping and a number of tone mapping operators have been developed to date. While these tone mapping operators (e.g. [2, 5, 11,12] among others) allow for displaying high-dynamic-range (HDR) images in a recognizable and even aesthetically pleasing way, nobody would confuse a photograph rendered in this fashion with, say, watching the same scene through a window. The dynamic range of conventional displays is simply inadequate for creating a visual sensation of watching a real sunset or driving a car into oncoming traffic at night. To ease this problem, a new class of high dynamic range displays has recently been demonstrated [10], which allow for a contrast ratio of more than 50000:1, and have peak intensities in the range of 2700 cd/m^2 to 8500 cd/m^2, while lowering the black level to 0.05 cd/m^2. For comparison, traditional displays usually reproduce a contrast of about 300:1 with a luminance range of approximately 1-300 cd/m^2.

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1.2 High Dynamic Range Display Technology

The principle underlying a high dynamic range (HDR) display is the use of a specialized spatially varying high-intensity backlight for a transmissive LCD panel [10]. In other words, light is filtered twice, once in the backlight, once in the front LCD panel. In one of the implementations of this fundamental idea, the image projected by a Digital Light Projector (DLP™) was used as backlight, in another a grid of high-intensity white light emitting diodes, each of which could be controlled individually. If the maximum contrast of the backlight image is c_1:1, and the maximum transmissive contrast of the front LCD panel is c_2:1, then the theoretical contrast ratio of the overall system is ($c_1 \cdot c_2$):1. The maximum luminance of such system will increase linearly with the maximum luminous power of the backlight.

Both HDR display prototypes mentioned above employed only a monochrome spatially varying backlight as color perception does not extend to high contrast ratios. Another interesting property of the above presented display systems is that the resolution of the backlight image can be lower than the front panel. This is based on findings from the field of psychophysics, which show that for contrasts higher than 150:1 cannot be perceived by humans at high spatial frequencies [13], i.e. within a small spatial area (e.g. the area covered by one LED of the backlight at typical viewing distances [10]). However, on a global scale humans can perceive much higher contrasts, and HDR displays can indeed display such images.

Displaying images on such a screen then requires the following technical steps:

- Obtaining a linearly encoded high dynamic range image (*radiance map*).
- Generating the background image.
- Generating the foreground image.

1.3 Motivation for High Dynamic Range Projectors

In the last few years, we have seen data projectors capable of displaying images with contrasts of several hundred-to-one. Although such dynamic range is adequate for motion pictures, computer generated graphics and multimedia; there are other potential applications, which could benefit from increased dynamic range, such as visual perception experiments, medical research, and virtual reality simulators. In cases like these, the ability to project a high-dynamic range image onto almost arbitrary surfaces is useful. An additional benefit is that the surfaces, onto which the images are projected, do not need to contain any metal, which is important in the environments that use magnetic tracking devices or MRI equipment.

In the original implementations of the HDR displays, a flat LCD panel is used as the display surface and faces the viewer. This severely limits the maximum size of such displays, as larger LCD panels (say more than 30" diagonal) are currently still considerably more expensive.

Another reason for desirability of projection-based displays is geometric design constraints for projection surfaces. Even though most projection systems are designed to form an image on a flat surface, it is relatively easy to alter the optics to enable projections onto curved surfaces, such as domes or cylinders. Such surfaces cannot be handled with display-based technologies.

2 PROJECTION-BASED HDR DISPLAY SYSTEM

Here, we will present a novel approach to significantly increase the dynamic range of the existing Digital Mirror Device-based data projectors.

2.1 Design Decisions

Like in an existing display system for HDR images, described in [10], the idea is to modulate the light intensity more than once.

2.1.1 Integrated vs. Separate Unit

One common natural desire when designing things and using them is to have everything in one compact unit. The disadvantages of such approach can be multiple. First, there are few ways to modulate light intensity that are free of side effects. E.g. if high image contrast is not needed, the second modulator should display a spatially uniform image.

However, the image may still be affected by the second modulator, as some light may be lost, and some will be scattered. This will respectively reduce the image brightness and decrease the contrast.

2.1.2 Choice of Modulators

As mentioned, in order to achieve contrast higher than is possible with existing devices, one needs to modulate the light more than once. There are two[1] major alternatives for light modulation, suitable for creating an image: Liquid Crystal Displays (LCD) and Digital Light Processing (DLP™). Each of them has their own distinct properties.

LCD panels contain a film of liquid crystals, sandwiched between the transparent electrodes and two polarizing filters. The presence of two polarizing filters alone in this structure significantly reduces the maximum transmittance of the modulator to about 15-20%. Due to use of polarizers, it is not always practical to combine two or more of such modulators in sequence, as adjacent polarizers need to be aligned for optimal performance. Furthermore, one would have to create a collimated light beam the size of the sandwiched panels to make this idea work.

DLP™ technology is implemented via use of microchips. Such microchips contain a microscopic mirror for each pixel that can be quickly (~15 μs) rotated between two orientations through the controller circuitry built into the chip. One orientation directs a collimated beam of light towards the imaging optics, creating a bright spot on an image; another directs it towards a light absorbing material within the projector. To obtain intermediate pixel intensity levels, the mirror orientation is pulsewidth modulated (PWM) [3]. DLP™ technology by itself is already capable of relatively high contrast ratios, with commercially available projectors demonstrating ANSI contrast ratios of several hundred-to-one. Unlike LCD, DLP™ chips are significantly more optically efficient, with early models passing as much as 60% of the light when ON [3]. However, sequentially combining more than one DLP™ chip to achieve higher contrast is not possible, as two PWM modulations running simultaneously don't give the correct result (the momentary state of the pixel at the end will be a logical AND operation of the states of the corresponding pixels in all DLP™ chips on the path).

As a result of the above constraints, we decided to use a DLP™ projector with an additional LCD panel and optics between the projector and the screen for our prototype.

2.2 Description of the System

The light beam exiting a normally functioning projector is diverging, in order to be focused into an image some distance away. However, in order to combine, that is, to optically multiply the transmission ratios, the real images created by one modulator must be focussed on the other. In an integrated system, this could be accomplished, by aligning an LCD panel with a DLP™ chip. In our prototype, this requirement has led to the following design (Figure 1).

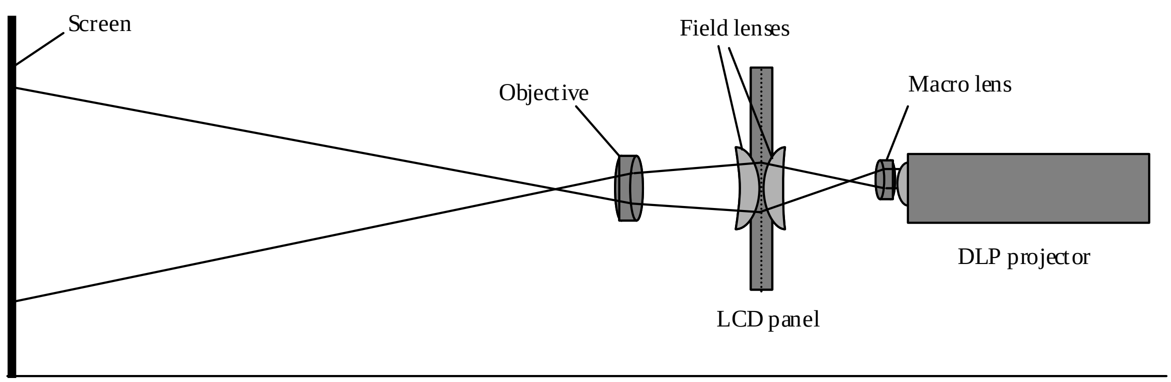

Figure 1: HDR projection system.

[1] One additional technology also exists, called Liquid Crystal on Silicone (LCOS), which consists of liquid crystals and corresponding polarizers deposited directly on a highly reflective substrate. Applying voltage to the liquid crystals allows light to be either reflected from the chip surface or absorbed, concept similar to DLP. Colour is usually created via use of three chips for each primary. The technology is very young, relatively expensive, and has optical properties somewhat similar to those of LCD-s.

We used an *Optoma EP755* DLP™-based projector. Its colour wheel was removed to increase the maximum light output, as in an earlier HDR display prototype [10]. The projector has a 1024-by-768 resolution, contains a 200W UHP (ultra-high-pressure mercury) lamp and is specified to have a 2000 lm output and a 600:1 contrast ratio. We used a digital DVI interface to connect it to one of the outputs of a PC video controller. As the projector's optics are designed to create an image more than one meter away, we added a 100 mm focal length achromatic lens directly in front of the projector to enable it to project a (smaller) image about 100 mm away.

Then, the image created by the projector (Figure 2) is focussed onto[2] an LCD panel. Originally, the intention was to employ the type of LCD panel used in Personal Digital Assistants (PDAs). As had been discussed above, a secondary modulator can be monochromatic and need not have the same high resolution as the primary one. For example, one of the HDR display designs uses 760 white LEDs, arranged in a hexagonal grid, as a backlight (for details see [10]). Thus, a small, monochrome display of a typical PDA (about 50x50 mm) would have enough resolution for this application. However, driving such a display would require development of a controller. Hence, we opted to use a *Sharp QA-75* computer projection panel, designed to be used with old overhead projection units, as it accepts regular VGA input. As this panel is larger than needed, we use only a small central portion of it, about 40-by-30 mm, or 120-by-90 pixels (see Figure 2).

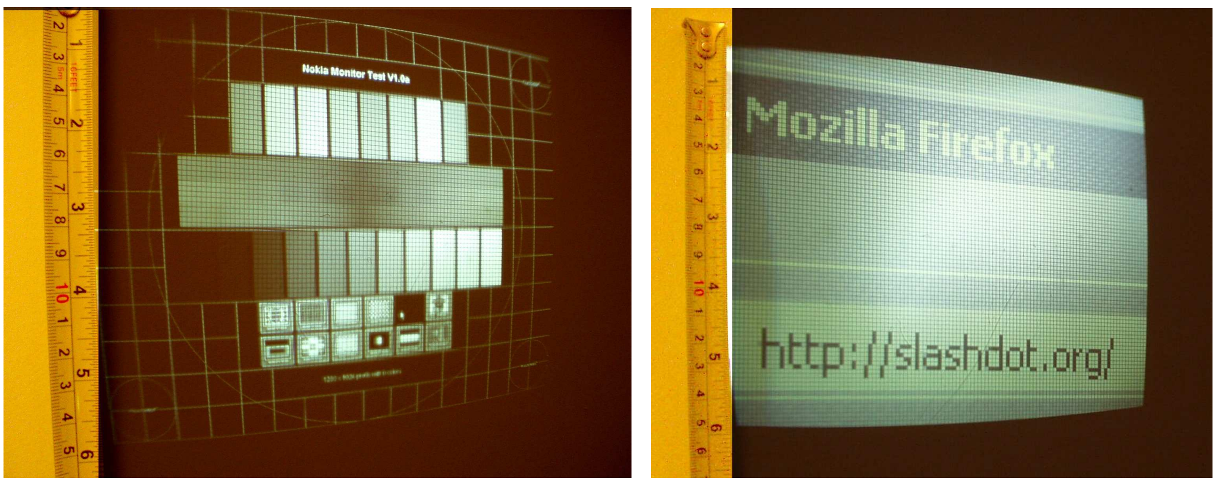

Figure 2: Left: image created by the projector passed through a transparent LCD panel. Right: LCD panel image while the projector is displaying a white background; note the lower resolution of the LCD image. Also note the grid visible in both images, created by the LCD panel. The left portion of each image has been artificially brightened to show the measuring tape.

As the rays after passing through the panel would continue to diverge, in order to aim them into the objective lens, we used two 120 mm plano-convex lenses, acting as a "field" lens.

Finally, a single achromatic lens with a focal length of 125 mm was used to project the composition of the two coinciding images, – of the original DLP™-chip inside the projector, and that of the LCD panel, – onto a white wall, about 70 cm away.

2.3 Driving the System

The algorithm for driving the system was adapted from [10]. The essential idea is that one would like to minimize the quantization errors between the intended luminances and the displayed luminances.

First, we start by determining the luminance response of the projector and the LCD panel. In our specific case, the external LCD panel has a substantially lower contrast ratio than the projector. Then, the inputs c_1 and c_2 for both of the

[2] Actually, the alignment is intentionally made imperfect, to blur the grid lines of the LCD panel, in order to eliminate moiré patterns.

components can be described by a following set of equations, which ensure that the relative error is equally spread over modulators:

$$c_1 \cdot c_2 = c,$$

$$c_1 / c_2 = c_{1max} / c_{2max}$$

where c is the target transmission ratio of the system, c_{1max}, c_{2max} are maximum contrast ratios of the respective modulators.

Algorithm:

- Use the value determined from this equation for the LCD panel as is.
- Compute the image created by the LCD panel, by using its optical point spread function.
- Divide the target luminance by that image, pixel-by-pixel, to obtain the value with which to drive the projector.

The last step will ensure that the blurring of the pixels of the low-resolution LCD panel is compensated for.

3 MEASUREMENTS

3.1 Procedure

We used a Minolta LS-100 luminance meter for our measurements. For contrast measurements, we adopted the ANSI display testing procedure. The procedure specifies a 4x4 black-and-white checkerboard pattern (Figure 3).

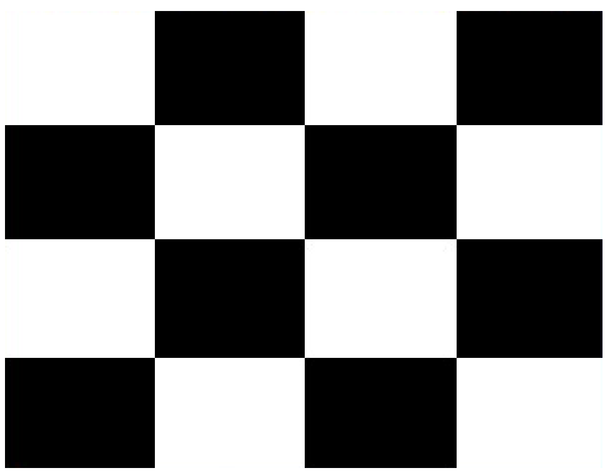

Figure 3: ANSI pattern for contrast measurement.

The contrast value is determined as the ratio of the average luminance of the white squares to the average luminance of the black squares. The contrast measured in projectors according to this procedure is always smaller than full ON/OFF contrast, and is considered to be fairer and more accurate, as it takes into account undesirable light scatter from white areas onto black areas, which invariably increases the black level and thereby decreases the contrast.

3.2 Results

Here, we present measurements of contrast, transmissivity, and luminance, associated with the HDR display system, as well as with each of the components of the system. All measurements took place in a completely darkened room. All surrounding surfaces, other than the white wall used as a screen, were covered with black cloth and computer monitors were switched off during measurements.

3.2.1 DLP™ Projector

For these measurements, the projector was positioned about 1.2 m away from the white wall. With the zoom set to "tele", the image size on the wall was 300-by-400 mm (approx. 12-by-16 inches).

Maximum luminance: 610 cd/m^2.

Minimum luminance: 4.5 cd/m^2.

ANSI contrast ratio: 136:1.

Note: the ratio is substantially lower than 600:1, quoted in the specification.

3.2.2 LCD Panel

Here, the values were determined through three measurements of luminance on the screen generated by the projector displaying a uniform white image: with projector only, with the LCD panel added to the path in "transparent" mode, and with the panel in "black" mode.

The following results were obtained:

Maximum transmissivity: 0.172.

Minimum transmissivity: 0.018.

ANSI contrast ratio: 9.56:1.

3.2.3 Complete System

The following measurements were taken when the system was fully assembled (as in Figure 1). The screen is about 90 cm away from the foremost lens. The image size is about 150-by-200 mm (approx. 6-by-8 inches).

Maximum luminance: 425 cd/m^2.

Minimum luminance: 0.6 cd/m^2.

ANSI contrast ratio: 708:1.

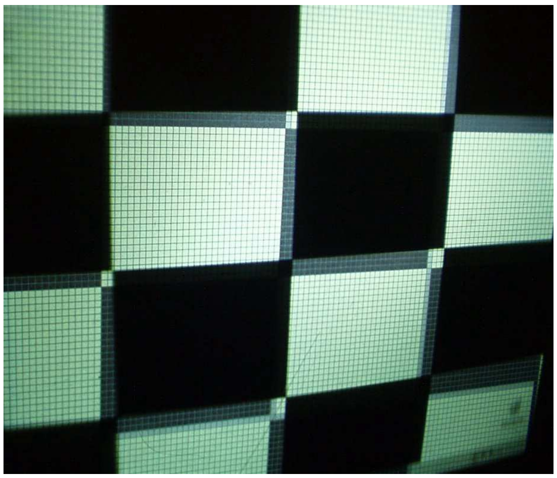

Figure 4: Display content when measuring the contrast. The projector image was offset slightly for this image to better demonstrate the effect of the double modulation.

4 ANALYSIS OF THE DESIGN AND IMPLICATIONS

As has been demonstrated, the addition of an LCD panel to the optical path of the DLP™-based projection system can noticeably improve the contrast ratio. In this section, we will discuss the strengths and the limitations of this design.

Our complete system produces a luminance level of 425 cd/m^2, which is about 4 times higher than the level of a typical desktop CRT monitor. However, this is still not sufficient to properly represent luminance values corresponding to directly visible light sources (sun: ~$1.6 \cdot 10^9$ cd/m^2), their specular reflections, or even diffuse white surfaces under sunlight (~$3 \cdot 10^4$ cd/m^2). Note that while the size of the obtained image was small, which worked in favour of the measurements, particularly maximum luminance measurements, we used a plain white wall as the "screen". Substituting it with a specialized front- or back-projected screen with a higher optical gain will markedly improve the peak luminance, allowing for a much brighter "white".

Since no new light is added to the system, an extension of the dynamic range is possible only into the dark regions. Phrased differently, the complete HDR projector can achieve significantly deeper "blacks" than the conventional projectors. This is under the assumption that the image size remains constant; otherwise, higher luminance can easily be achieved by optically decreasing the size of the projected image or by moving the screen closer to the projector. Another way of achieving higher maximum luminance is by using a "brighter" light source. The latter is not always practical, since the price increases very rapidly with higher light output. In our current implementation, we achieved substantially higher maximum brightness by removing the colour wheel of the projector, thereby limiting ourselves to black-and-white images of the overall system. Finally, using an LCD panel with greater transparency in the "white" state can also markedly improve the maximum brightness. While theoretically an LCD panel may transmit up to 50% of the light, almost all available monochrome panels transmit around 17% of the light and many colour models, like the one used in [10], are rated at around 7..8 %.

We achieved an ANSI contrast of 708:1. Admittedly, this is not very impressive compared to the specifications for HDR displays. The main reason behind this is the low contrast ratio of the LCD panel, which, when paired with a projector for overhead transparencies, was designed to be used for presentations at the times when self-contained data projectors were unavailable. Even a marginally better panel can improve this situation. On the other hand, note that even with such contrast, the black level remains reasonably low; as it is typically specified that 1 cd/m^2 is an acceptable value [10]. It also evident that the final achieved contrast is not actually the product of the individual contrast ratios, which would give approximately 1300:1. The discrepancy is most probably due to imperfections in optics, as we used very simple optical schemes and the lenses were not fully enclosed in a light-absorbing container. Both of the mentioned deficiencies can be easily dealt with in production. There is also a possibility that the low contrast that we achieved is an indicator that, at such high contrast ratios, the optics become a limiting factor. Two observations support this last statement: first, the lens that is the closest to the screen is responsible for the fidelity of the final image more than other individual components of the system; second, many modern projectors, which quote "ON/OFF" contrast ratios in the order of thousands-to-one, and which probably contain light modulators capable of such contrast, when measured with the ANSI method, demonstrate an ANSI contrast of only a few hundreds-to-one.

5 CONCLUSIONS AND FUTURE WORK

We described a method of increasing the dynamic range of a conventional data projector via the use of an external light modulator. The measured ANSI contrast of the new HDR projector was more than 700:1. While in the current incarnation the range of luminances and contrast ratios is modest, the overall outlook is promising. The system is designed as an external attachment to a regular DLP™-based projector, which allows the use of unmodified projectors and makes the system reasonably compact. We proposed some technical refinements to make the specifications more competitive with those for HDR displays.

As for the future work, it would be interesting to consider how an additional LCD modulator inside a current DLP™ projector could be used. This would significantly reduce the number of optical components in the system, compared with the current design and could allow for much higher contrast ratios.

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