P. 54.2: A High Dynamic Range Display Using Low and High Resolution Modulators

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Abstract

We have developed an emissive high dynamic range (HDR) display that is capable of displaying a luminance range of 10,000cd/m^2 to 0.1cd/m^2 while maintaining all features found in conventional LCD displays such as resolution, refresh rate and image quality. We achieve that dynamic range by combining two display systems – a high resolution transmissive LCD and a low resolution, monochrome display composed of high brightness light emitting diodes (LED). This paper provides a description of the technology as well as findings from a supporting psychological study that establishes that correction for the low resolution display through compensation in the high resolution display yields an image which does not differ perceptibly from that of a purely high resolution HDR display.

1. Introduction

The ultimate goal of digital display systems is to present images that are visually indistinguishable from the real setting they portray. Conventional display technology (LCD, CRT, plasma, etc) have achieved part of that goal by introducing both spatial resolution and refresh rates that are beyond the visual acuity of a human viewer. However, even the highest quality displays available today are incapable of showing the true luminance (brightness) range we perceive in real life. Every day we encounter light sources in our natural environment that are several orders of magnitude brighter than any conventional display. A typical fluorescent light fixture has a luminance of approximately 2,000cd/m^2 and on a sunny day objects illuminated by the sun can easily have luminance values up to 10,000cd/m^2. But current computer monitors can only display images within a luminance range of approximately 1cd/m^2 to 300cd/m^2, and as a result are unable to display luminance-realistic images.

2. High Dynamic Range Display

To overcome the dynamic range limitation of conventional displays, the HDR technology replaces the uniform backlight of an LCD by an active matrix array of ultra high brightness white LEDs. These current-controlled diodes are capable of emitting over 250,000cd/m^2 at maximum current and no emission in the off state with an effective 8-bit resolution between those states if driven by an 8-bit Digital to Analog Converter. The LED array then effectively constitutes a very low-resolution (5mm per LED), but very high brightness display. The low-resolution image of the LED array is then projected through a color LCD, which displays a similar, but high resolution, version of the image. This modification is described pictorially in Figure 1. The arrangement of the LED does not necessarily have to be as shown but can be hexagonal for closer packing or any other arrangement that is appropriate for the application.

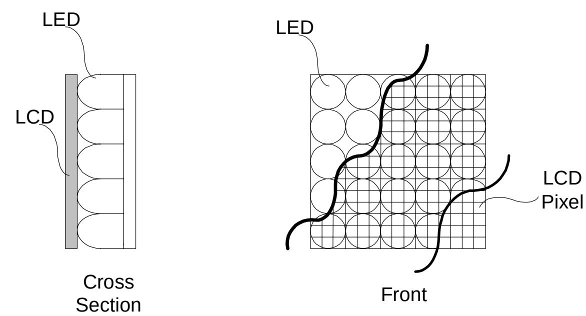

Figure 1. Layout of LED array behind color LCD

This double modulation then defines the boundary of the dynamic range of the HDR display. The darkest state is produced by a dark LED behind an LCD pixel set to black, the brightest state is produced by an LED driven at maximum current behind an LCD pixel set to maximum transmission. Such a 'multiplication' of two 8-bit display systems results in a 16-bit dynamic range with an adequate number of non-linearly distributed distinct luminance levels to create a smoothly addressable gradient per color.

3. Blur Correction Method

The optics of the HDR display have been designed such that each LED produces a smoothly varying illuminance pattern on the front display, with the luminance distribution of adjacent LCD overlapping to the extent required to yield fairly uniform luminance when all rear pixels are on.

As described, this leads to a perceivable blur of the final output image. This can be counteracted by appropriate corrections to the front image (i.e., the image on the LCD) since the nature of the blur is known. Based on a 16-bit input image, the display driver can establish the optimum setting for the LED array, which provides a known luminance distribution across the array. It is then possible to divide the 16-bit input image by the known LED array luminance distribution to get the image transmission values that need to be displayed on the LCD. Physically, these two images are multiplied as the light passes from each LED through a cluster of LCD pixels. This method will generally re-create the high-resolution image quality defined in the 16-bit input file. The exceptions are at very high contrast boundaries, where the dynamic range of the LCD is insufficient to make the appropriate image correction. The following example will illustrate the steps of this method.

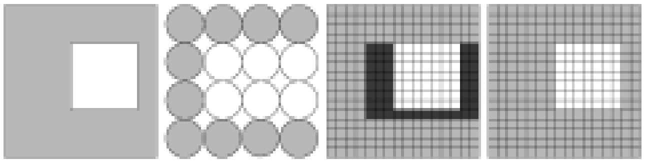

Figure 2. Composite Formation of HDR image. From left to right: Desired image, LED setting, LCD panel setting and final HDR image.

In Figure 2, we wish to display a picture of a bright square upon a dull gray background. On a regular monitor, the square would be a cluster of white pixels, and the gray box would be a cluster of gray pixels. When using the modified HDR technology, the boundary between the white and the gray falls on several 4x4 pixel clusters, each corresponding to a single LED. (For ease of visualization in this example the size ratio of LED to LCD pixel has been set to 1:4.) The LED behind the cluster has to be set to maximum brightness to make the white as bright as possible (assuming that the white square is as bright as the maximum output of the display). Conversely, the LEDs behind the gray border have to be set to a low output because the border isn't very bright. The small part of gray that happens to be in the 4x4 pixel group that also has the bright white light in it, and is thus backlit by the maximum brightness LED, has to be treated differently by the system. That gray region in that area will look a lot brighter than the gray in all the other 4x4 pixel groups. To counter this effect the system sets these apparently gray pixels to a significantly darker shade of gray in the image on the front LCD display, thereby reducing the final output to the same gray as the one in the neighboring 4x4 pixel groups. Basically, in the all gray 4x4 pixel groups we have a low-light LED modulated by a mediumly transmissive LCD pixel resulting in light gray while in the 4x4 pixel groups with some part of the white square in it we have a bright light LED modulated by a very weakly transmissive LCD pixel resulting once again in light gray.

Through this method it is possible to use a very low resolution backplane behind a conventional LCD display without losing resolution. This has several significant advantages. The lower resolution of the backplane drastically reduces the computational effort in computing and transmitting the image. The file size of HDR images thus does not have to increase at all (compared to conventional 8-bit image files) since the small amount of extra information for the backplane (less than 1% of the LCD resolution) can be stored in the available free space that is part of most conventional file formats (JPEG, TIF, etc). Furthermore, the extra information is small enough that no modification of the videostream from PC to display is necessary (i.e. there is no direct requirement for a 16-bit graphic card). Finally, such a design allows complete backward compatibility. A user with an HDR display and an HDR image file can enjoy the improved HDR image. A user with an HDR display but lacking the appropriate file can still easily view the full content of a conventional 8-bit image file (the front image component will be displayed and the HDR display, after not finding the small extra backplane 'tag' in the file, will set the LED array to some uniform luminance level to emulate a conventional 8-bit LCD display for the duration of that image). And a user with access to an HDR file but no HDR display can still view a very reasonably tone mapped representation of the image on the conventional display. (The display will simply ignore the extra HDR tag.)

4. Psychology Background

The human visual system has evolved to comfortably view a luminance range of 10,000cd/m^2 to 0.1cd/m^2. But even within the given range our brightness perception is not perfect. In particular, optical imperfections in our eyes limit our brightness perception, including scattering in the cornea, lens and retina, and diffraction in the coherent cell structures on the outer radial areas of the lens. These effects are responsible for the "bloom" and "flare lines" seen around bright objects. The diffraction effect causes a lenticular halo, which is ignored in this project as it does not significantly impact the perceived image.

Bloom [1] (often termed "disability glare" or "veiling luminance") is the result of light scattering in the ocular media contributed roughly equally from the cornea, crystalline lens and retina scattering. Figure 4 illustrates an example of bloom. Light from source A scatters inside the eye onto the same receptors as if coming from source B, thus adding an effective luminance L_e. Since light is added to both the dark and light parts of B, the effective contrast ratio L_2/L_1 is reduced. The magnitude of L_e depends on the angle of separation α and the luminance and solid angle of the source.

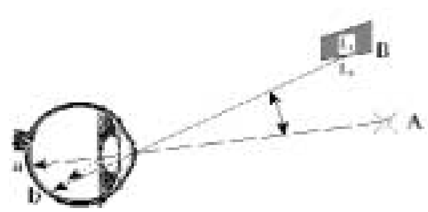

Figure 3: Bloom effect due to intraocular scattering.

Empirical psychophysics research led to a point spread function P(α) for the bloom effect [1].

$$P(\alpha)=\eta\delta(\alpha)+\frac{c}{f(\alpha)}$$

Equation 1: Bloom Point Spread Function.

The constant η represents the fraction of the light that is not scattered and δ(α) is the ideal point spread function. k is an empirically determined calibration constant. The function f(α) has been successfully modeled to very high precision with a first order term of $f(\alpha)=\alpha^2$.

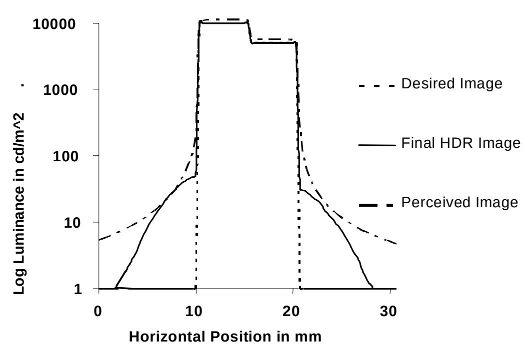

Figure 4. Comparison of display and eye introduced blur at a contrast boundaries of 0cd/m^2 to 10,000cd/m^2, 10,000cd/m^2 to 5,000cd/m^2 and 5,000cd/m^2 to 1cd/m^2.

Using this model and the average constants as outlined, it is possible to approximate the perceived luminance pattern corresponding to each image on the HDR display. In particular, the model provides a description of the perceived blur at each high contrast boundary. As long as this perceived blur is more significant than the image degradation of the HDR display due to lack of LCD dynamic range, then no degradation will be perceived. For the blur introduced by a 5mm LED at a viewing distance of 30cm or more, this will be the case.

5. Psychophysical Validation

In order to validate the predictions of the psychophysical model described above, we have carried out a test with 20 observers. The test included two stages of comparison of real and test images. The images used were a photograph of the Stanford Memorial Church (a 16-bit image) and a test image designed to show all possible boundaries between 16 luminance levels, each twice as high as the last. All images were shown as pairs on a 15" screen size at a viewing distance of 50cm.

The first stage was designed to validate the general claim that high dynamic range images appear more realistic and pleasant than low dynamic range images shown on a conventional display. For this comparison, the test image and the real scene were shown side by side in a random arrangement of low and high dynamic range settings. The low dynamic range image was presented on the high dynamic range display by setting the rear modulator (i.e. the low resolution image plane) to a uniform gray level of the same brightness as a conventional LCD backlight. This leaves only the dynamic range of the front image plane for modulation of the light and thus emulates the display capabilities of a conventional LCD, since the front image plane is simply such a conventional LCD.

The second stage was designed to provide empirical data for the degree of discomfort und unrealism, if any, associated with the blur introduced by the rear modulator. In order to vary the degree of blur in the rear modulator we replaced the matrix of LEDs with a monochrome digital mirror projector whose light passes through a Fresnel lens and the appropriate diffuser before reaching the LED. Optically this is the equivalent of the LED matrix but with the benefit of control over the resolution of the rear modulator. In this stage, the subjects were exposed to two adjacent high dynamic range images of the same scene (either the real scene or the test image). One of the two images was randomly chosen to be the reference image featuring a resolution match between the front and rear modulator (i.e. the same high resolution at both the LCD and the projection with pixel by pixel alignment of both images). The other side of the test image presented the same scene but with a varying degree of blur in the rear modulator. The blur was created by blurring the image data for the projector. The appropriate blur correction image was then displayed on the LCD. At a 5mm blur this is equivalent to the blur introduced by the LED backplane. We investigated 4 different sizes of the low-resolution 'pixel' (2.5mm, 5mm, 10mm, 15mm).

For each set of images, the participants were asked to provide ratings on 5 semantic differential bipolar adjective pairs (*bright - dim, interesting - monotonous, sharp-smooth, pleasant – unpleasant, realistic - unrealistic*). The last scale (*realistic-unrealistic*) was omitted for the test image. In general, we expected that high dynamic range image would be considered brighter, less uniform, more interesting and more realistic than corresponding low dynamic range images. In the comparison of blurred and reference high dynamic range images we expected that the blurred images would be perceived as progressively smoother and potentially less pleasant and less realistic with increasing blur. For the comparison of blurred and reference images there could be a small difference in the perception of brightness. The artefact halos introduced by the blurred image at high contrast boundaries could trigger a perception of brightness as our visual system considers halos of this kind to be indicators of bright areas.

6. Results – Display Performance

A fully functioning prototype of the HDR display was constructed using a 6" diagonal color LCD and a 16x12 LED array. The prototype uses a 2% transmissive LCD and is capable of showing a maximum brightness of over 3,000cd/m^2. We have tested the setup with commercially available 7% transmissive LCD (such as those found in most laptops) and measured a maximum brightness of over 10,000cd/m^2.

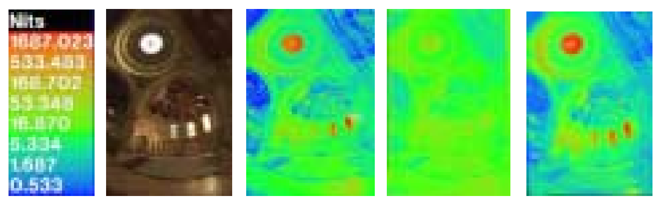

Figure 5. Luminance maps of the memorial church high dynamic range image. From left to right: Scale, image tone-mapped to 8-bit, false-color of original 16-bit image, conventional display (NEC MultiSync XE21), HDR display.

7. Results – Psychophysical Validation

The first stage of the HDR display quality test provided the anticipated results. Low dynamic range (i.e. 8-bit) images were perceived as significantly less bright, less interesting and somewhat less pleasant and less realistic. Perception of the sharpness of the image was unaffected by the reduction from 16-bit to 8-bit as one would expect given that both images where shown at the same spatial resolution.

The comparison of non-blurred and increasingly blurred high dynamic range images indicated that no degradation of the image was perceived even with significant blur of the rear display. In particular, we did not observe any decrease in the perception of sharpness of the image in the range of blur sizes used in the test (2.5mm to 15mm). Instead, the blurred images were consistently observed as sharper than the non-blurred high dynamic range image. We believe that this is the result of the blur compensation features found in the front display which might slightly overcompensate for the blur in the rear display. Such overcompensation could lead to very slight dark edges around bright areas and slightly lighter edges around dark areas. This effect is unnoticeable during close inspection of any particular area but might leads to a crisper overall appearance of the image.

All other scales (brightness, interest, pleasantness and realism) followed approximately equal trends and consequently all four scales will be treated as a general quality scale in the following. The blurred test pattern was perceived to be of equal quality as the non-blurred test pattern through the entire range of increasing blur from 2.5mm to 15mm. This result is consistent with the psychological model of intraocular scattering and the assumption that even very large blur size will not lead to perceptible degradations even in fairly artificial scenes composed effectively entirely of sharp high contrast boundaries.

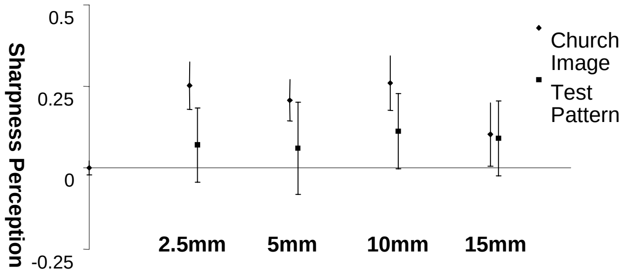

Figure 6. Sharpness ratings at increasing blur of the rear display. A rating below 0 (up to -0.5) indicates that the 8-bit image was perceived as less bright than the non-blurred 16-bit image and vice versa for ratings above 0 (up to 0.5).

At small blur sizes, the Memorial Church image was perceived to have higher general quality than the non-blurred version of the image. This higher quality perception diminished with increasing blur size and at 15mm both the blurred and non-blurred images were perceived to be of approximately equal quality. We believe that the higher quality perception at small blur sizes is the result of sub-pixel misalignment of the two display layers which would lead to a small loss of high spatial frequency contrast in the non-blurred image. This effect does not occur in any blurred image since the effective pixel size of the rear display is so much higher than the pixel size of the high resolution display that sub-pixel misalignment becomes insignificant.

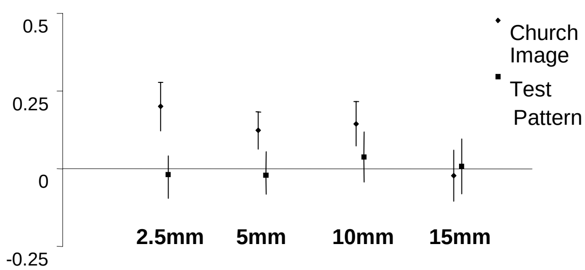

Figure 7. General quality ratings at increasing blur of the rear display.

The test results provide statistically significant support for the postulate that 2.5-15mm blur of the rear display does not degrade the perception of sharpness or general display quality. In addition, it is clear from the first stage of the test that 8-bit low dynamic range images are perceived as vastly inferior to realistic 16-bit high dynamic range images.

8. Future Work

The presence of an active backlight offers additional opportunities to enhance the performance of the display and overcome several challenges of conventional LCD displays. Two such challenges are motion blur and color gamut problems of the LCD technology. Due to the low refresh rate of LCDs it is often impossible to show moving objects without a motion trail. Several display manufacturers have proposed a solution to this problem [2]. By appropriately flashing the backlight in sync with the LCD, it is possible to significantly reduce motion blur. This operation is challenging if the backlight is a conventional fluorescent tube (or array thereof) but simple if the backlight already is an active matrix array of multiplexed LEDs.

Similarly, the use of LEDs in the backplane overcomes the critical limitations of the LCD color gamut [3]. It is possible to replace the white LEDs with combined red, green and blue LEDs which are driven as single elements. Such RGB LEDs provide a spectrum with three narrow peaks at red, green and blue, allowing for a significantly better color gamut than LCD or even CRT displays. Like the solution of the motion blur problem, this benefit comes at almost no additional cost and effort as a natural consequence of using the HDR technology.

9. Conclusion

The HDR technology yields a significantly enhanced representation of real scenes by portraying the entire visual range that is comfortably accessible to humans, with the added potential of an increased color gamut. It does so without any noticeable banding of luminance steps or any degradation of other characteristics of conventional LCDs (resolution, refresh rate, etc). In particular, despite the physical imperfection at high contrast boundaries due to the lower resolution of the LED array, there is no perceived blur at those boundaries necause such effects are masked by intraocular scattering. As a result, the HDR display is perceptually free of degradation across the entire 10,000cd/m^2 to 0.1cd/m^2 luminance range. It is clear that 16-bit images are significantly more desirable than 8-bit images and consequently any 16-bit display is desirable. But the HDR display with low and high resolution modulators not only offers 16-bit image quality but achieves this high dynamic range without the need for a 16-bit videostream and without the costly requirement for two high resolution display layers. These advantages come at no discernable image quality cost.

10. Acknowledgements

The authors thank Paul Debevec for providing the Stanford Memorial Church high dynamic range photograph used in the psychophysical test. Further thanks goes to Thomas Wan for assisting with the design and implementation of the viewing test.

11. References

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[2] Bruinink, J. et al, Improved Motion-Picture Quality of LCD TV, SID Symposium 2002

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