Self-Calibrating Wide Color Gamut High Dynamic Range Display

Helge Seetzen[1/2], Samy Makki[1], Henry Ip[1], Thomas Wan[1/2], Vincent Kwong[1], Greg Ward[1], Wolfgang Heidrich[2], Lorne Whitehead[2]
[1]BrightSide Technologies, [2]University of British Columbia

ABSTRACT

High Dynamic Range displays offer higher brightness, higher contrast, better color reproduction and lower power consumption compared to conventional displays available today. In addition to these benefits, it is possible to leverage the unique design of HDR displays to overcome many of the calibration and lifetime degradation problems of liquid crystal displays, especially those using light emitting diodes. This paper describes a combination of sensor mechanisms and algorithms that reduce luminance and color variation for both HDR and conventional displays even with the use of highly variable light elements.

Keywords: High dynamic range, display, contrast, color correction, calibration

1. INTRODUCTION

Our natural environment features a very wide range of luminance levels. On a sunny day it is easily possible to see bright areas exceeding 10,000cd/m^2 next to shadow regions below 1cd/m^2. Our visual system has evolved in this environment to give us approximately 4-5 orders of magnitude of simultaneous dynamic range perception. Adaptation can further increase this range over longer time periods. Our visual system evolved in this environment and in general viewers prefer imaging devices with similar capabilities [Seetzen 2006a].

Conventional displays cannot match this high dynamic range. Plasma and Cathode Ray Tube (CRT) displays are inherently limited to a modest luminance range. Liquid Crystal Displays (LCD) use an array of light elements behind the LCD panel and can therefore in principle achieve higher luminance by increasing the intensity of the backlight elements. Unfortunately the contrast of LCD panels is limited to less than 1,000:1 so any increase in the peak luminance through this method will also raise the black level of the LCD to unacceptable levels. Moreover, increasing the backlight intensity also requires the use of additional light elements in the backlight which leads to issues such as luminance uniformity, differential ageing of light elements and color variation when colored light elements are used. This is especially true if light emitting diodes (LEDs) are used instead of the currently common cold cathode fluorescent (CCFL) light elements.

Recent years have seen the emergence of High Dynamic Range (HDR) displays to overcome this limitation of conventional displays [Seetzen 2003]. HDR displays are capable of presenting very high contrast images by varying the intensity of the backlight according to the image content. The most common variant of these displays uses an array of LEDs as the backlight for an LCD panel. The LEDs are controlled individually or in small clusters to locally modulate the luminance of the display while the LCD imposes higher resolution modulation as well as color modulation. Together, the two modulation elements provide a very high dynamic range. With this design, the problem of unacceptable black levels is removed as the backlight can achieve very high luminance levels in some areas while remaining completely black in others.

The choice of LEDs as the light source for LCD offers a number of benefits such as thermal load reductions and environmental considerations. Actively modulating the LED array yields further benefits, such as reduced power consumption and longer lifetime [Seetzen 2006b]. Nevertheless, the above mentioned issue of color and luminance variations remains a concern. The luminance and color of LEDs varies significantly between different production batches and also during operation as the LED experiences different temperature and lifetime conditions. The current solution to this problem is to sort LEDs at the factory. This reduces fixed variations at a significant cost premium but

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does not address lifetime changes. This paper presents a calibration technique that makes use of the unique features of HDR displays to remove the variation concern and leverages several other benefits of actively modulated LEDs. A variant of this approach can be extended to conventional LCD displays to reduce luminance variation.

2. HIGH DYNAMIC RANGE DISPLAY DESIGN

The design principle underlying HDR displays requires the use of two modulation layers in series. This can be achieved by backlighting a conventional LCD with an array of modulated LEDs or small clusters thereof. In this arrangement, the LED array projects a low resolution luminance pattern onto the back of the LCD panel. That pattern approximates the desired output image of the display and is modulated further by the detailed high resolution image on the LCD.

Most of the benefits of the HDR display derive from the interaction of the two modulation layers. For example, the contrast of the HDR display is given by the product of the modulation range of the LED array and LCD panel. To achieve these benefits without introducing visible image artifacts, it is necessary to compensate for the low resolution of the LED array with the LCD image. The basic approach for this modulation can be found in Figure 1 [Seetzen 2004].

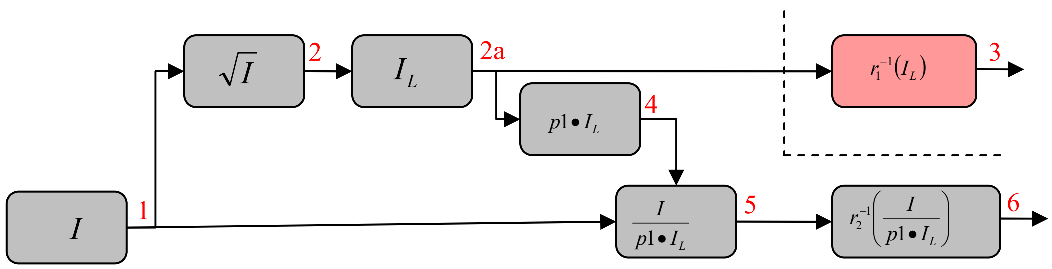

Figure 1: Image processing algorithm for HDR displays

The incoming image (1) is first separated into components for the two modulators using a square root or similar function. To determine the drive information for the LED array, the image is then reduced in resolution, mapped onto the geometric layout of the LED array and sent to the LED array. The next step is to calculate the anticipated light field (4) generated by the LEDs by summing up the contributions of each LED to the total light field. The point spread function (PSF) of each LED is adjusted by the drive value of the LED, the response function of the LED, and any other necessary factor such as thermal or lifetime calibration. It is important that the PSF used in this process accurately reflects the effective light distribution of one LED, including any interaction with the optics and films used in the package. The result of this summation is a simulation of the light field of the LED backlight for this input image.

Finally, the LCD image can be generated by dividing the input image by the light field simulation (5). If the LED backlight uses LEDs with different spectral components to achieve a wider color gamut, then these need to be simulated as well, and the division occurs per color channel. For a white LED backlight, on the other hand, the RGB input image is divided by a monochrome light field. In both cases, the result of the division is adjusted by the inverse response function of the LCD.

At this point, the image processing algorithm is finished and the HDR display can show a complete frame. The LEDs will be driven to the appropriate intensity and the LED backlight will create a luminance distribution that is similar to the light field simulation. The LCD will modulate this luminance distribution such that the final output will match the input image.

3. CALIBRATION MECHANISM

The dual modulation approach of the HDR display relies on the multiplication of two serial modulation layers. As described above, this process amounts to an identity operation and should therefore yield accurate images. However, this process relies on a well calibrated LED backlight. If the light field simulation in step (4) of Figure 1 does not match the actual light field generated by the LED array then the final image will not be accurate. The discrepancy between target and actual image is relatively minor if the difference between simulated and actual light fields is primary one of luminance, as our eyes are relatively forgiving for smoothly varying luminance gradients. This is not the case for color variations at the spatial frequencies corresponding to the LED spacing [Pattanaik 1998]. Such differences are easily registered by the eye.

Local or global color variations in the LED backlight can have many causes and are common, even in conventional non-modulated backlights where they produce undesirable color patches and other artifacts. For LED backlights, this problem is further aggravated by the wide chromaticity variations found in LED manufacturing. Figure 2 shows the chromaticity range of a standard white LED line. Clearly this range is undesirable overall and will lead to very significant image artifacts for HDR and normal displays.

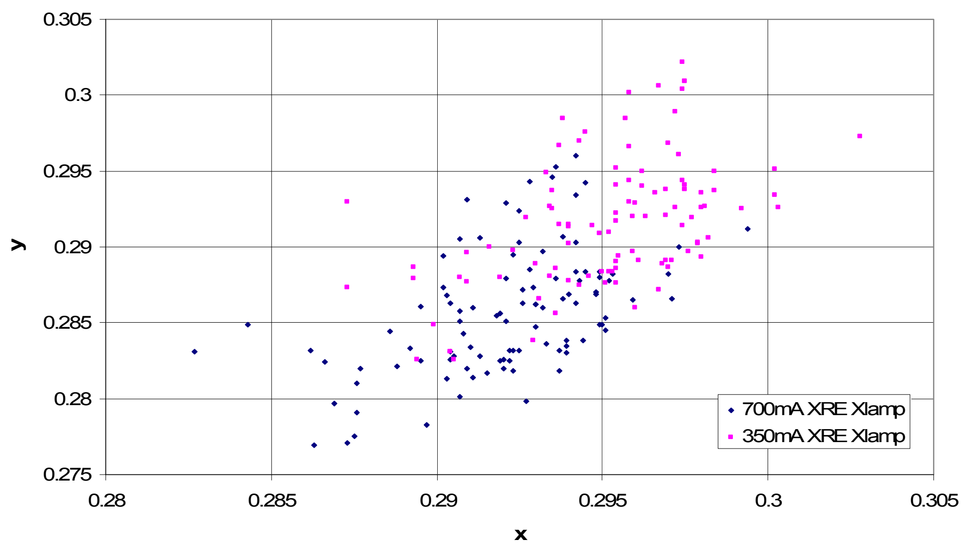

Figure 2: Chromaticity coordinates of Cree XRE XLamp at different currents. Note that these LEDs are from the tightest bin available and nevertheless span a wide chromaticity range. The chromaticity shift at different drive currents illustrates further variation encountered during operation which is made worse by other effects such as thermal and lifetime degradation.

The current solution to this problem is to sort LEDs at the factory into bins of certain chromaticity ranges. This process is expensive and furthermore, leads to a large portion of unusable LEDs in the less desirable bins. Binning also does not solve the color variation problem because it is not economically possible to sort LEDs into chromaticity bins that match our perceptual capability to distinguish color variations.

The HDR display design offers an opportunity to solve the color variation problem because the light field simulation can be adjusted for known color and luminance variation. The LCD image can then be used to correct for the variation in the same way that it corrects for the low spatial resolution of the LED backlight. This process requires two elements that are described in more detail in the following section: A sensor mechanism to characterize the color and luminance variation of the backlight and an image processing algorithm to make the appropriate corrections to the LCD image.

3.1. SENSOR MECHANISM

There are two sources of color variation: manufacturing variation and operating variation. Manufacturing variation can be the result of LED chromaticity variations, non-uniformities in the optical layers of the backlight, LCD mura and a number of other sources. The common characteristic of these variations is that they are fixed at the point of assembly of the HDR display. Operating variations occur during the life of the HDR display and include effects such as differential aging of the LEDs, thermal dependence of color and luminance, LED failure and other effects that occur at different time scales during the life of the display.

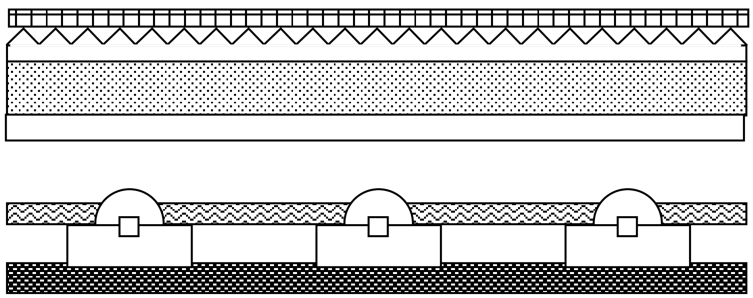

Figure 3: Optical package of the HDR display including LCD (1), micro-structured films such as BEF or DBEF (2), diffuser (3), wave guide (4), cavity (5), reflective film (6), LED (7) and circuit board with heat sink (8)

The first step in calibrating an HDR display is to characterize all manufacturing variations. Fortunately, it is not necessary to investigate the source of the variation or the interplay between different effects because only the final output of the HDR display matters. A common method to characterize the variation is to take two to four low resolution, high dynamic range color images of the fully assembled HDR display. These cameras are already used in conventional LCD manufacturing to detect mura and other display artifacts [Pratt 1998]. For this measurement it is necessary to set the LCD image to a uniform grey screen and enable a subset of the LEDs for each of the two to four images. The camera needs to extract individual color values for each LED so each sub-image needs to have a checkerboard pattern of LEDs. If, for example, the width of the PSF of each LED is substantially zero on top of neighboring LEDs, then only two images are required (both with every second LED enabled and shifted by one LED from the first to the second LED). An algorithm can then extract the color and luminance characteristics of each LED in the backlight from the images. This information is stored in the image processing logic of the HDR display for later use by the correction algorithm. This information also provides a baseline against which operation variations can be referenced.

The compensation of operating variation is more complicated and requires internal sensor systems as it is undesirable to recalibrate the HDR display with external tools during operation. A common way to measure backlight spectral and luminance variation is to use one or more photosensors coupled with appropriate color filters to measure the luminance and chromaticity variation of each LED as it ages. It is unfortunately too expensive to install such sensors in every small area of the backlight and certainly not practical to install a sensor at each LED. Instead, only a small number of sensors can be used at the edge of the HDR display by placing a planar light guide into the optical cavity of the display. Figure 3 shows such an arrangement where a clear light guide is placed between the LED and LCD panel. Through the use of small diffuse regions on the light guide, it is possible to trap a very small portion of light from each LED in the plane where it will propagate to the edge of the plane as a result of total internal reflection. With this arrangement, it is possible to periodically re-measure each LED by turning off all LEDs and illuminating one LED at a time. Depending on the drive mechanism for the LED array, it is possible to execute this measurement at each image frame. For example, if the LEDs are driven with a pulsed modulation scheme, then each LED or LED region can have a slightly different phase so that at any moment in time only one LED is active. Drive schemes that cannot achieve high frequency patterns of this type can still use this technique by, for example, measuring only a small portion of LEDs at each frame and gradually measuring the entire LED array over multiple frames in this fashion.

The actual light level reaching the sensor from a particular LED depends on the distance and geometry. It is therefore necessary to reference ongoing measurements against the standard obtained during the factory measurement. Since the losses in the light guide are fixed during operation of the HDR display, it is possible to calculate the effective luminance and color variation of an LED during operation by comparing the factory data with ongoing reading. These values are unaffected by environmental changes as a display backlight is generally sealed from dust and other outside influences.

Example:
During the factory calibration of an HDR display, it is found that at the centre of the display the LCD has a blemish that reduces transmission by 15% and that the LED behind that central region is 10% brighter than the luminance target of the display. The sensor read-out for this LED during factory calibration is 0.5 units.
The blemish is a static feature of the LCD and will therefore be considered for all image processing in the future by ensuring that either the LED or LCD in this region will be driven 15% higher than normal. The higher luminance of the LED will also be captured and during operation the LED will be driven 10% lower than normal.
During operation the sensors will continuously sample the LED in the fashion described above. A year after leaving the factory the LED might have aged to the point that the sensor reads 0.4 units. Comparing this to the factory reference indicates that the LED luminance has dropped by 20% from 0.5 to 0.4 sensor units and the LED will consequently be driven 10% higher than the normal level.
The same process is possible for chromaticity variation by replacing each luminance sensor with a color sensor and considering each color channel separately during both factory and lifetime calibration.

This process of factory and ongoing calibration referenced against factory values makes it possible to accurately track the luminance and color development of the LED backlight. In turn, this allows for an accurate simulation of the backlight light field that can then be corrected by the LCD image. The following section describes the correction algorithm in detail.

3.1. CORRECTION ALGORITHM

As described above, only the final output of the HDR display needs to be accurate and for any output level, there are many options to adjust the LED backlight and LCD image without changing the final output. This gives the correction algorithm significant freedom to adjust both modulation layers. In general, it is desirable to run the LED backlight at the lowest level in each region and compensate as much as possible with the LCD. This reduces the power consumption of the HDR display, the thermal load for the backlight, and minimizes further aging effects on the LEDs.

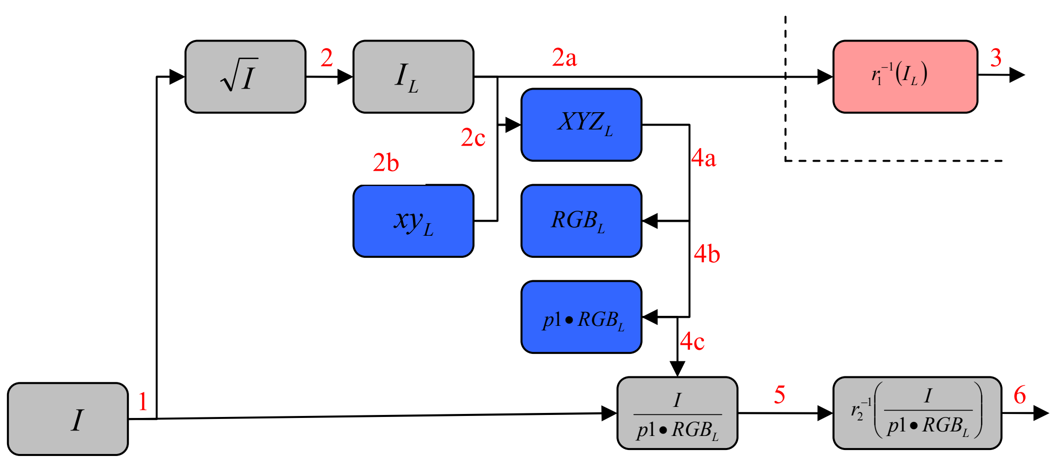

Figure 4: Enhanced image processing algorithm for HDR display with color correction

The correction algorithm is an enhancement to the basic HDR display algorithm described in Section 0 and relies on the same system parameters such as the geometry of the backlight, the response curve of the LEDs and LCD, and the spectral characteristics of the system. Furthermore, the correction algorithm uses the information obtained during the factory calibration described above. Figure 4 shows the basic steps of the enhanced image processing pipeline.

The factory calibration extracts color characteristics of each LED as xy values (2b). Those values represent the chromaticity of each LED. Ongoing computations can be simplified by transforming the xyz values into an RGB representation of the luminance and chromaticity of the LEDs in the color space of the display.

The LED driving levels (2a) are calculated from the input image as described in Section 0. Those values are passed to the LED controller to drive the LEDs (3) and will be used in the image pipeline to determine the LCD image. The driving levels correspond to luminance levels Y and together with the xy chromaticity pair of the LED, a triplet Yxy is defined for every LED. The Yxy values can then be transformed into XYZ (2c) using the following equations:

$$X_r = x * \left(\frac{Y_r}{y} \right) \tag{1}$$

$$Y_r = Y_r \tag{2}$$

$$Z_r = (1 - x - y) * \left(\frac{Y_r}{y} \right) \tag{3}$$

In order to transform from the XYZ space into the desired RGB color space, a transformation matrix must be constructed from the primaries and white point of the display. Characterizing these values for a HDR display requires several steps because each LED in the backlight and the affected section of the LCD in front effectively becomes a small independent display. Each of these imaginary displays is defined by its own primaries and white point. The values are initially obtained during factory calibration. During subsequent operation of the display, the LED chromaticity and luminance will change and the sensor mechanism described in Section 0 can be used to periodically measure and update the individual characteristics of the LEDs.

Despite the separation into small imaginary displays, all LED values need to be transformed into the same color space to ensure that a specific RGB color is defined in the same fashion across the simulation of the backlight. The best choice for this common color space is the minimum gamut derived from all LED sections measured during factory calibration. Once the overall gamut is defined, it is possible to construct the transformation matrix that transforms every XYZ value into RGB values of the overall color space (4a).

The next step is to create a colored light field simulation (4 b). The image processing pipeline without color correction described in Section 0 creates a monochrome light field simulation to compensate for the low resolution of the LED backlight. With color correction enabled, the light field simulation uses the calculated RGB values to scale and adjust the point spread function of the LEDs. The result after the summation of the colored and scaled contributions of each LED is a colored light field simulation of the backlight. This greatly reduces the color difference between simulated and actual light field, especially for backlights using wider LED color bins. With this information, the algorithm can then execute the normal image processing steps with the appropriate color and luminance corrections.

Finally, the input image is divided by the light field simulation and adjusted by the inverse response function of the LCD (5) similar to the standard image processing described in Section 0. After this division, the LCD image compensates for the lower resolution of the LED array and local color variation of the LEDs.

4. RESULTS

The accuracy of the sensor mechanism described above can be very high without a significant cost impact. The accuracy of conventional luminance sensors is usually higher than other variations in a display design such as the stability of the drive mechanism. A 37” prototype design using eight TAOS TSL252R sensors placed at the edge of the wave guide reduced luminance variation to less than 2% across the display (except deliberate effects such as vignetting, as explained below). The number of sensors can be reduced further without significantly impacting the stability of the system but the low sensor cost makes it convenient to include a sensor on each circuit board of the display backlight. It is also possible to use integrated color sensors to achieve chromaticity calibration. A prototype design using six Hamamatsu S9032-02 RGB sensors achieved less than 4% variation per color channel across the display. Both results were obtained with large LED bin ranges and over a wide range of temperature conditions. This compares very favorably to conventional LCDs (CCFL and LED based) which generally feature variations in the range of 10-25% even with sorted LEDs in the backlight. Either of these implementations of the sensor mechanism therefore supplies very accurate information to the correction algorithm.

The main goal of the color correction algorithm is to minimize color variations. The human eye is very sensitive to color variation at the spatial frequencies corresponding to the LED spacing, especially in bright areas and success of the calibration technique is defined by the absence of perceptually visible color artifacts on the display. Figure 5 shows the difference between a corrected and an uncorrected HDR display. The level of correction, especially for green and blue variations, is clearly visible.

Figure 5: Color of a 46” HDR display for a medium grey input image before (left) and after (right) the correction algorithm is applied. For print reproduction of this paper both image have been adjusted with a 4x saturation enhancement filter. The maximum color variation before adjustment is 14% in the green channel (bottom right corner) and 7% in the blue channel (distributed in several areas across the screen). After calibration all channel are uniform to within less than 1%.

The additional computational costs for this technique are linear and very low because calculation of the values of the LED and LCD component is already necessary in the basic implementation. Added to this base line are a few extra steps for every LED, which is a very inexpensive procedure compared to the light field simulation.

The downside of this technique is the loss of luminance in the corrected regions of the image. The amount of luminance being decreased depends on the color shift of the LEDs and the input image. The maximum luminance loss occurs with a white input image and a LED with a maximum difference to the image white point. Color correction therefore adds a parameter to the operating variations of the luminance uniformity. This can be compensated during runtime by calculating the loss and adjusting the driving level of the LEDs accordingly.

Error! Not a valid bookmark self-reference. provides an example of the luminance field before and after color correction. The after correction the luminance across the screen is very uniform. The edges of the display are dimmed by the HDR image processing algorithm in order to simulate vignetting, which the viewer is used to from conventional displays. The luminance in the bottom right corner of the display is substantially reduced compared to the uncorrected display because the correction of the color variations is very intense in this area.

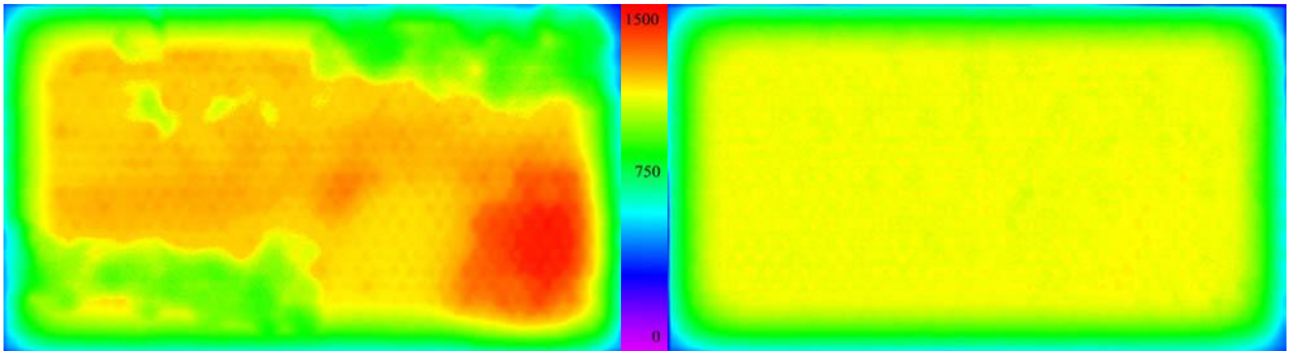

Figure 6: Luminance uniformity before (left) and after (right) color correction using a linear false color scale from 0cd/m^2 to 1,500cd/m^2. Notice the significant drop in luminance in the bottom left quadrant to achieve overall uniformity.

Using the LCD screen as the correction filter also decreases the bit depth of the original image slightly. Color steps that are required for the correction need to be removed from the input image. Fortunately, similar to the luminance loss described above, the maximum bit depth loss will occur using a white image input and the LEDs with values furthermost from the desired average white point. In most TV applications, the incoming image will have a much lower bit depth (e.g. 8 or 10 bit) compared to the HDR display system bit depth (14 to 16 bit) so this effect can be ignored. For true HDR images being shown on HDR displays, the effect is generally not visible either as the bit depth of HDR images is generally higher than our perceptual ability to resolve individual steps at the high end.

5. CONCLUSION

The combination of sensor and calibration mechanisms described in this paper provides a low cost technique to significantly improve luminance and color stability of direct-lit displays. A small number of sensors combined with an optical waveguide allow continuous sampling of light elements in the backlight. Variations among those elements can then be compensated for either by adjusting the driving level of the elements or by appropriate adjustments to the LCD on top of the affected region. The first option is possible in HDR displays, which have active modulation capability for the backlight elements and can therefore use both approaches to further reduce the power consumption of the display. For displays with static backlights, it is generally not possible to adjust the drive level of individual elements and the correction therefore needs to occur on the LCD.

The use of these techniques provides sufficient compensation capability to significantly lower the need for sorting backlight elements into specific color and luminance bins. This reduces cost and manufacturing complexity – two of the major obstacles for full penetration of LED backlights. Overall, these advantages make it possible to develop very high precision HDR displays and calibrated conventional displays at lower cost, lower power consumption, better image stability and lower manufacturing complexity.

6. ACKNOWLEDGMENTS

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