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## Abstract

*In dual layer high dynamic range displays, images are formed through the optical modulation of a front panel image by a backlight image. We present a colorimetric method for calculating the backlight image that maximizes gamut utilization while minimizing quantization errors, producing displayed images with deeper, more saturated colors.*

## 1.      Introduction

High dynamic range (HDR) displays are currently being developed that enable the photometrically accurate presentation of scenes with luminance contrast exceeding 100,000:1. The high contrast ratio of these displays is achieved through a dual layer design wherein light is modulated in two stages. In the design presented by Seetzen et al. [1], an initial image is formed by a spatially addressable LED backlight. In the second stage, an LCD front panel optically modulates the backlight image, producing a final image with increased dynamic range. Another design uses a spatially uniform backlight, but incorporates two LCD panels in series to produce an HDR projector [2]. Other designs are also possible, but all operate under the same principle of dual modulation. Associated with this is an inherent image processing problem that must be addressed in any dual layer HDR display. In order to produce a final target image, intermediate images must be calculated for each stage. The process of generating these images is known as image splitting and the image processing employed can vary depending on the viewing requirements of the display and its construction.

Prior research has been conducted on image splitting with the aim of minimizing parallax errors that arise when viewing a dual layer display from an off-axis position [3,4]. However, this research and the general analysis of HDR displays thus far have been restricted to luminance only. In this paper we present a colorimetric model for dual layer displays and reexamine the problem of image splitting in this context. An analysis of the model reveals that a new image splitting strategy must be employed in order to fully utilize the most saturated colors.

## 2.      Display Construction

The display used in this research was constructed following the design of Seetzen et al. [1]. The RGB front panel selected for the display came from an Apple Cinema 30" LCD. A high-resolution achromatic backlight was created by tiling a pair of Planar PR5022 DLP projectors. The projectors were modified by removing the color filter wheel and disabling white peaking to eliminate any additional color processing for non-primary segments. Only a basic alignment of the projectors and front panel is needed, as an automatic camera-based registration establishes a mapping between layers with subpixel accuracy. Additional elements placed between the backlight and front panel were a 1m focal length Fresnel lens to concentrate light in an optimal viewing position and a diffusing sheet to increase the acceptable viewing area.



**Figure 1. Prototype display with high dynamic range content.**

## 3.      Colorimetric Model

Imai et al. [5] have previously presented a model for colorimetric characterization of HDR displays incorporating RGB color modulation in both image layers. Due to their use of a DLP projector with its color filter wheel in place, a spectral model utilizing eigenvector analysis was proposed. This model allows the use of a RGB color projector without any modifications, but at the added cost of modeling complexity and some unresolved error in the reproduction of bright orange and yellow colors. Depending on the specific projector used, and its filter wheel design, other errors may be seen in practice, making the general performance hard to predict.

Eliminating the DLP color filter wheel allows a much simpler model to be used. Our work builds upon a standard LCD colorimetric model presented in Day et al. [6]. This model was selected because it accurately predicts the response of the front panel with a mean CIEDE2000 color difference, $\Delta E_{00}$, of 0.24. The model is extended for the HDR display by the addition of a multiplicative factor with black offset for the backlight:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \left( \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \times \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{bmatrix} X_k \\ Y_k \\ Z_k \end{bmatrix} \right) \cdot \left( A(1 - A_k) + A_k \right) \quad (1)$$

The matrix is composed of the XYZ tristimulus values for the RGB primaries of the LCD front panel. The $XYZ_k$ term accounts for the black offset of the LCD. The linear backlight signal, A, has a range of [0,1] and is scaled so that the actual multiplicative factor has a range of $[A_k,1]$. The offset, $A_k$, is to account for the minimum light output from the projector.

## 4.      Display Gamut

In order to calculate the gamut volume of an HDR display, it is necessary to evaluate the model at fourteen RGBA coordinates. The upper limit of the gamut is defined by the RGB primaries, CMY secondaries, and maximum white with A equal to 1. The
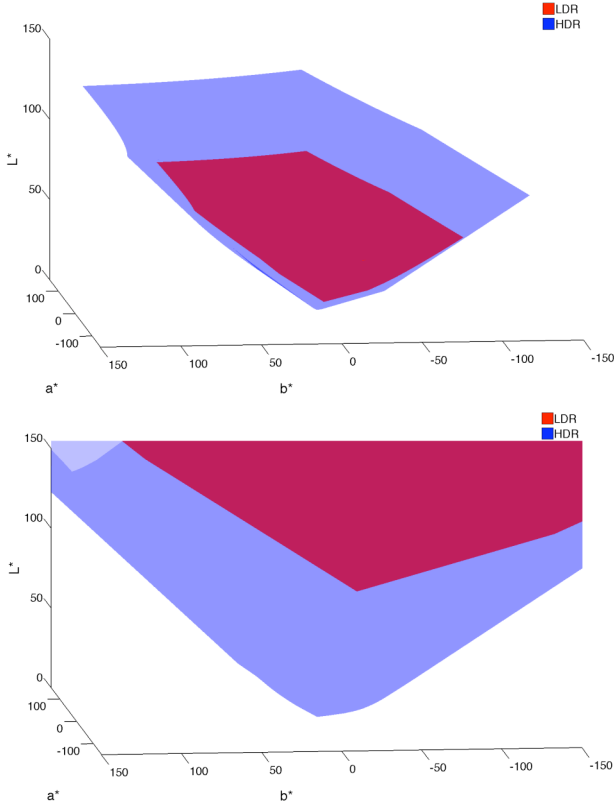
**Figure 2. LDR (red) and HDR (blue) CIELAB gamuts for bright image content (top) and dark image content (bottom).**

lower limit of the gamut is defined by the RGB primaries, the CMY secondaries, and minimum black with A equal to 0. The convex hull of these points defines the gamut volume in XYZ space. This volume is then transformed to CIELAB coordinates. The choice of white point for the transformation should reflect a state of adaptation appropriate for the image content being displayed. Because HDR displays can accurately render content over a large range of luminance, the transformation to CIELAB is performed once with a high luminance white point appropriate for bright content and once more with a low luminance white point appropriate for dark content. Figure 2 shows plots for both conditions along with a conventional LDR display gamut for comparison.

The LDR gamut was generated using the primary matrix and black offset measured for the HDR display, but holding the backlight signal, A, at a constant value appropriate for a conventional LCD. A comparison of the gamuts shows that not only does the HDR display have a much greater contrast ratio, but it also has improved black rendering with the ability to maintain high saturation even in very dark image content. This advantage of HDR displays is not apparent in a luminance only analysis and serves as the motivation for reexamining image splitting with extra attention to color reproduction in dark scenes.

## 5.     Image Splitting

Because the input to the colorimetric model has four dimensions, whereas the output has only three dimensions, there are several potential solutions to the image splitting problem. In practice, a perfect solution may not be achievable due to resolution
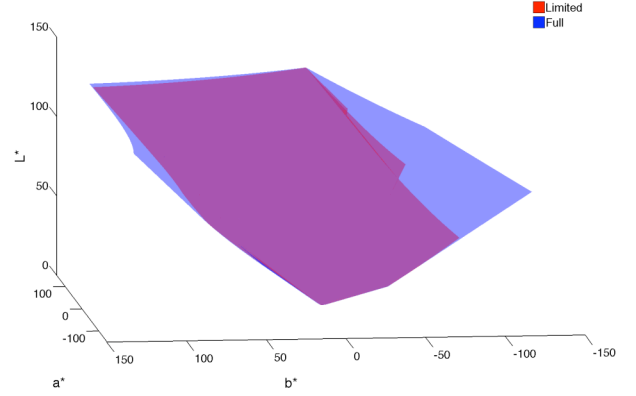


**Figure 3. Blue regions indicate colors that become inaccessible when using the luminance square root to generate a backlight image for full color displays.**

differences between image layers or the constraints of real time processing. A successful image splitting algorithm should minimize distortion of the target image while being simple enough to incorporate in a real time system.

### 5.1.     Luminance Only Image Splitting

One simple strategy for image splitting is to calculate the square root of luminance and use this to drive the backlight. This has served as the foundation of Trentacosta et al.'s [7] work, wherein a target image for the backlight is calculated by this method and then approximated using a low-resolution LED array. Similarly, Guarnieri et al. [3] start with the luminance square root and apply spatial filtering to reduce parallax errors in a stacked monochrome LCD display.

One argument for using the square root is that it uniformly distributes quantization errors across the two layers. This is true if both layers use identical components as with stacked LCDs. However, hybrid designs that mix different display technologies, such as DLP with LCD, may benefit from asymmetric splitting.

### 5.2.     Full Color Image Splitting

Attempting to use the luminance square root a an image splitting strategy without modifications on a full color display severely limits the range of the gamut that can be utilized. The reason is that as the target XYZ value moves away from the display neutral, the peak luminance achievable for that chromaticity decreases. If no efforts are made to normalize for the peak luminance along that direction, the backlight signal will be too low and the front panel will not have sufficient headroom to compensate for bright colors. The effect of this on gamut utilization is shown in Figure 3 and is most pronounced along the blue primary.

One way to extend the square root method to full color displays is to compute the square root along the dominant primary. The dominant primary is calculated by inverting the matrix from Equation (1) and multiplying by the target XYZ value. The RGB component with the largest value is the dominant primary and can be used to calculate the square root for the backlight:

$$A = MAX \sqrt{\left( \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix}^{-1} \times \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \right)} \qquad (2)$$
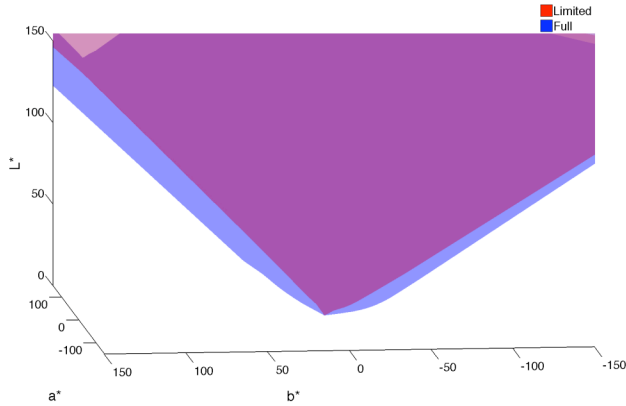
**Figure 4. Blue regions indicate colors that remain inaccessible in dark image content even after modifications to normalize the square root calculation for full color displays.**

This modification solves the problem with headroom for bright colors. However, it is an approximation that does not take into account the black offset in each stage. Even with a correction for the black offset, it will still underutilize darker colors near the edge of the gamut. The loss of saturated colors for dark image content is shown in Figure 4.

## 5.3. Model-Based Image Splitting

Deep, saturated colors continue to be inaccessible even with a modified square root calculation because the most saturated colors in a dual layer display are uniquely determined in RGBA space. The correct profile for A values along the faces of the gamut is linear with respect to luminance. This linear profile "locks" the RGB values of the front panel into their most saturated state wherein at least one component will be equal to 1 and one component will be equal to 0. The remaining component will be somewhere between [0,1]. Another way of phrasing this is to say the back plane carries the entire burden of luminance modulation for the most saturated colors. Any square root-like, or non-linear, calculation will generate the wrong curve shape for A and result in underutilization of the gamut. Therefore a colorimetrically optimal image splitting algorithm should transition from a square root like profile for colors near the neutral axis to a linear profile for colors at the edges of the gamut. This will maintain the benefits of uniformly distributed quantization for most colors while still allowing the full gamut to be utilized.

Analysis of the colorimetric model in XYZ space is performed to generate a smooth transition from square root to linear behavior. For any target XYZ value, a plane can be constructed that contains the target XYZ value, maximum white, and minimum black. Slicing the display gamut along this plane yields the boundary depicted in Figure 5. Drawing a line from the origin through the target XYZ value produces an intersection with the surface at the upper limit of the gamut. Two values need to be determined based on this line. (1) The relative position of this intersection between maximum white and the edge of the gamut, called *s*. If the line intersects the white point, *s* equals 0. If the intersection lies at the edge, *s* equals 1. At any position in between, *s* is scaled linearly. (2) The relative position of the target XYZ along this line, called *t*. If the target XYZ is located at the top of the line, on the upper limit of the gamut, *t* equals 1. If the target XYZ falls at the bottom of the line, on the lower limit of the gamut, *t* equals 0. Like *s*, *t* is scaled linearly along this line.
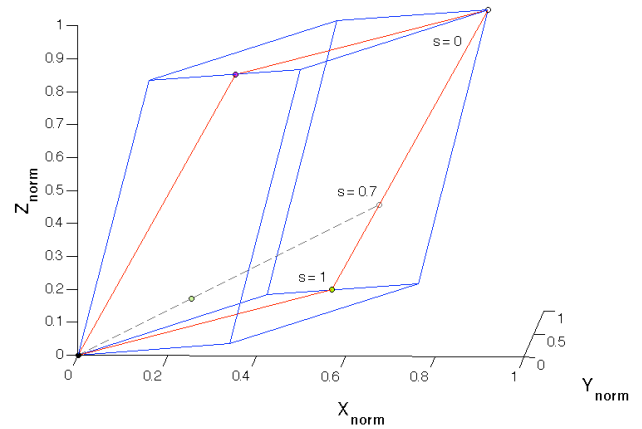


**Figure 5. HDR display gamut in normalized XYZ coordinates. The red boundary is the plane containing the target XYZ, maximum white, and minimum black. The dashed line runs through the target XYZ and the point of intersection, *s*, controls the transition from square root to linear backlight.**

Because the calculation of the plane is highly unstable for target XYZ values falling near the neutral line, it is not explicitly calculated. Instead, the endpoints of the intersecting line are calculated by inverting the model given in Equation (1) with the conditions that A equals 1 for the top intersection and A equals 0 for the bottom intersection, and that the chromaticity values of the intersections match the chromaticity values of the target output. The values of *s* and *t* can then be calculated as described above. From *s* and *t*, the backlight value A is calculated as follows:

$$A = \frac{t}{\sqrt{t} \cdot (1-s) + s} \tag{3}$$

The denominator in this expression represents the contribution of the front panel to luminance. At the edge of the gamut, the denominator is always 1, indicating that the front panel contributes a fixed amount. Along the neutral line, the denominator is equal to the square root of *t*. In between, it is a linear weighting of these two limits. The contribution from the backlight image, A, is then the fraction of *t* that is not satisfied by the front panel.

## 6. Implementation

In order to use the model-based image splitting method described above in a real time display, some optimizations must be made. Analysis of the algorithm reveals that the only computationally expensive stage is solving the inverse problem for Equation (1) to find the intersection points with the top and bottom of the gamut. Because these intersections depend only on chromaticity, this step can be performed in advance and stored in a compact 2D LUT using the target chromaticity as the index. For more perceptually uniform sampling, the LUT is calculated in terms of CIE 1976 u'v' chromaticity rather than xy chromaticity. With the inverse problem precalculated and stored in the LUT, the values of *s*, *t*, and A can then be computed rapidly.

## 7. Conclusions

Existing techniques for HDR image splitting that only consider luminance produce a backlight image that limits the utilization of highly saturated colors. We have presented a colorimetric image

splitting technique that allows the full volume of the HDR display to be utilized. Using this technique to generate the target backlight image allows dual layer HDR displays to produce images with deeper, more saturated colors.

## 8. Acknowledgements

## 9. References

[1] H. Seetzen, W. Heidrich, W. Stuerzlinger, G. Ward, L. Whitehead, M. Trentacoste, A. Ghosh, A. Vorozcovs. "High dynamic range display systems," ACM Transactions on Graphics (Proc. SIGGRAPH '04) **23**, 760-768 (2004).

[2] A. Pavlovych, W. Stuerzlinger. "A High-Dynamic Range Projection System," Proc. SPIE Photonic Applications in Biosensing and Imaging, vol. **5969**, p. 59692O (2005).

[3] G. Guarnieri, L. Albani, G. Ramponi. "Image splitting techniques for a dual layer high dynamic range display," Proc. SPIE Medical Imaging 2008: Image Perception, Observer Performance, and Technology Assessment, vol. **6917**, p. 69170M (2008).

[4] G. Guarnieri, L. Albani, G. Ramponi. "Minimum-Error Splitting Algorithm for a Dual Layer LCD Display—Part I: Background and Theory," J. Display Technol. **4**, 383-390 (2008).

[5] F. H. Imai, D. Kuo, R. J. Motta. "Colorimetric characterization of a HDR display system," Proc. of the 10th Congress of the International Colour Association AIC Colour '05, Granada, Spain, 653-656 (2005).

[6] E. A. Day, L. A. Taplin, R. S. Berns. "Colorimetric characterization of a computer-controlled liquid crystal display," Color Research and Application **29**, 365-373 (2004).

[7] M. Trentacoste, W. Heidrich, L. Whitehead, H. Seetzen, G. Ward. "Photometric image processing for high dynamic range displays," J. Visual Communication and Image Representation **18**, 439-451 (2007)