Colorimetric characterization of a HDR display system

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ABSTRACT

A spectral-based High-Dynamic-Range (HDR) display model that estimates colorimetric XYZ tristimulus values from sextuplets of digital signals consisting of triplets of values for Liquid Crystal Display (LCD) monitor and triplets for the Digital Light Projector (DLP) is proposed. An inverse transformation is also provided based on an initial split followed by a search procedure using derived forward model. The forward model was reasonably accurate except in very bright and chromatic yellow and orange colors. The inverse transformation also provided reasonable performance except for out-of-gamut and very bright colors.

1. INTRODUCTION

In order to take advantage of the increasing presence of high dynamic range (HDR) acquisition systems, such as our Pixim DPS,[1] it is necessary to improve the dynamic range capabilities of current displays by orders of magnitude. Seetzen et al.[2] have presented different display systems capable of displaying images with dynamic range typical to what is seen in the real world. One of the proposed display systems is based on a combination of off-the-shelf components consisting of a Digital Light Projector (DLP) an LCD panel. This HDR display is based on a dual modulation principle, where the LCD panel is used as an optical filter that modulates a high intensity but lower resolution image coming from the DLP projector. We have implemented a system very similar to Seetzen's et al, with the notable exception that while the original design of the HDR display required the filter wheel of the DLP projector to be removed in order to reduce light loss, in our own design we kept the filter color wheel in place. This eliminated unnecessary problems of electronic synchronization and increased the color gamut of the HDR display system. Increasing the color gamut was not the main motivation for building this display such as in the multi-primary display systems available to render spectral images.[3,4] Rather, the goal was to build a display system that provides sufficient gamut to reduce color matching errors and thereby allow side-by-side comparisons to support our work on HDR rendering algorithms. In order to improve the image viewing angles, a diffuse surface was set against the front of the LCD panel holding it with a glass panel. The display used a lenticular-type sheet in addition to the diffusion sheet to redirect more light to the viewer. As a result, we achieved a modest 1300 cd/m2 off the display, rather than the higher intensity that has been demonstrated in other systems.[2] Besides intensity reduction, another drawback of the use of color filters in the DLP projector was the complexity of its colorimetric calibration.

The colorimetric characterization can be divided in a forward model that estimates XYZ tristimulus values from devices red, green and blue signals and inverse model that estimates DLP projector and LCD display sextuplets from XYZ. Several models have been proposed for the LCD display colorimetric characterization[5] and DLP colorimetric color management[6] but no characterization research has been performed in a high-dynamic range display system constituted by both DLP and LCD panel. One of the greatest roadblocks for an accurate characterization is the fact the most common type of DLP projects uses a fourth clear filter besides red, green and blue. Therefore, a white linear signal has to be estimated from red, green and blue of the projector. This white channel is used to increase intensity when red, green, blue values surpass a certain threshold. A preliminary experiment with a HDR display forward model based on solely colorimetric measurements was found to be inaccurate particularly in the low light region. This happened because two reasons. First, it is unfeasible to collect all possible combinations for the sextuplets (e.g., for 8 bit displays, it will result in 6^{256} that is more than 281 trillion combinations) resulting in coarse sampling. Secondly, it was not possible to collect very accurate colorimetric measurements when the stimulus was very dark and data has to be extrapolated for this region. Moreover, inverse transformations based on search algorithms using this forward model resulted in images with color cast in dark regions. In order to overcome these problems, a model that is more accurate and robust, based on physics, was necessary. This article describes our methodology for building the forward model based on spectral radiance measurements and also presents an inverse transformation from colorimetric values to device digital signals.

2. METHOD

The spectral radiance $S_{\lambda,HDR}$ coming out form the LCD panel with attenuation function $T_{\lambda,LCD}$ can be written as:

$$S_{\lambda,HDR} = S_{\lambda,DLP} \bullet T_{\lambda,LCD}, \qquad (1)$$

where $S_{\lambda,DLP}$ is the spectral power radiance from the DLP reaching the back of the LCD panel. The λ subscript denotes that the matrices represent spectra and the symbol $\bullet$ denotes point wise, element-by-element multiplication. From the additivity of the red, green, blue and white channels of DLP, it is possible to write:

$$S_{\lambda,DLP} = \sum_{i=1}^{4} S_{\lambda,i}, \qquad (2)$$

where $S_{\lambda,i}$ corresponds to the contribution of each of 4 channel spectral radiances. From the additivity of the red, green and blue channels of the LCD panel we have:

$$T_{\lambda,LCD} = \sum_{j=1}^{3} T_{\lambda,j}, \qquad (3)$$

where $T_{\lambda,j}$ corresponds to the attenuation transfer function for each of 3 channels in the LCD panel. Combining Equations (1) to (3), it results in:

$$S_{\lambda,HDR} = \sum_{i=1}^{4}\sum_{j=1}^{3} S_{\lambda,i} \bullet T_{\lambda,j} \qquad (4)$$

Eigenvector analysis was applied to each of twelve $S_{\lambda,i} \bullet T_{\lambda,j}$ elements for all digital levels in 8 bits (0 to 255) in order to reduce dimension and consequently get more robust transformations from digital signals to spectra. As a result, the first three eigenvectors $E_{\lambda,i,j}$ that accounted for most of the energy were sufficient to reconstruct spectral radiance element very accurately. This procedure was repeated for each of the twelve spectral radiance elements. It is possible to derive by regression 12 sets of coefficients $C_{i,j}$ with dimensions 3 by 256 by 256 that takes any combination of 256 levels of channel *i* of DLP and 256 levels of channel *j* of LCD panel and when combined with the corresponding eigenvectors $E_{\lambda,i,j}$ estimates $S_{\lambda,i} \bullet T_{\lambda,j}$ spectral radiance element as follows:

$$S_{\lambda,i} \bullet T_{\lambda,j} = E_{\lambda,i,j} C_{i,j}(D_{DLP,i}, D_{LCD,j}), \qquad (5)$$

where $D_{DLP,i}$ and $D_{LCD,j}$ are respectively quantized digital signals from DLP channel *i* and LCD channel *j*. In other words, $C_{i,j}$ is a two-dimensional look-up-table that relates pairs of quantized digital signals to eigenvector coefficients that are used to estimate spectral radiance in conjunction with corresponding eigenvectors. The eigenvectors $E_{\lambda,i,j}$ and coefficients $C_{i,j}$ can be calculated *a priori* from spectral measurements and each resulting $S_{\lambda,i} \bullet T_{\lambda,j}$ are summed to estimate the total HDR display spectral radiance. XYZ values can be easily calculated from spectral radiance. It is possible to be more efficient by bypassing the estimation of spectral matrices, that is time and space consuming, cascading matrices and estimating directly XYZ tristimulus values from pairs of *i* and *j* channels, respectively from DLP and LCD panel as follows:

$$XYZ_{HDR} = \sum_{i=1}^{4}\sum_{j=1}^{3} P_{i,j} C_{i,j}(D_{DLP,i}, D_{LCD,j}), \qquad (6)$$

where $P_{i,j} = \mathrm{K} M_{\lambda} E_{\lambda,i,j}$ is a 3 by 3 matrix, where K is a scaling coefficient, M_{λ} contains the color matching functions Using the spectral method, we were able to compute the XYZ values at lower luminance values with a higher confidence level as compared to measuring the XYZ values directly, which approached the limits of the operating range of our equipment

The inverse transformation is based in three parts. At first, we performed an initial split using a gamma curve with exponent 0.3 for the projector digital values normalized between 0 and 1, and used its inverse for the LCD values. Then, the LCD panel and DLP values were quantized from integer values between 0 to 255 and forward model is used to perform a search of the LCD panel signals assuming that the DLP signals are accurate. Finally, a refinement was run for the projector values for the sextuplets with LCD values that are close to 255 and which are yielding luminance Y values that are too low.

We built our HDR display system using a 17-inch ViewSonic VA720 LCD panel and a BenQ DLP. Both DLP and LCD panel were set on an optical table with a black fabric covering the light path. The distance from DLP lens tip and the back of the LCD panel was 85 cm. Spectral radiance measurements were performed in dark surroundings using Photo Research PR-650 spectroradiometer. At first, we measured the spectral radiance from DLP reaching the back of the LCD panel by setting the spectroradiometer lens tip 150 cm apart from the center of a card coated by barium sulphate that we used as our standard white. The white card was set parallel to the back of the LCD panel and the spectroradiometer was set behind the DLP. Ramps of red, green, blue and gray (i.e., when red, green and blue levels were same) were measured. The ramps for the white clear channel were calculated by subtracting the sum of red, green and blue channel spectral radiances from gray spectral radiances.

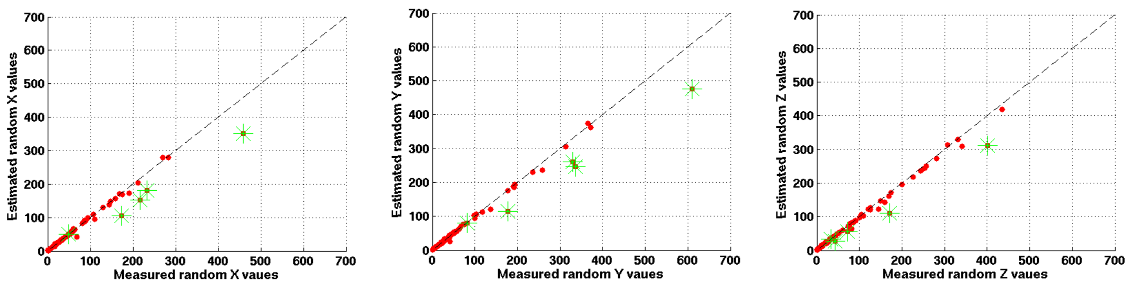
Next, we measured the spectral radiance from the front of the LCD panel setting the lens tip of the spectroradiometer 45 cm apart from the LCD panel pointing perpendicularly to its center. The lens was slightly defocused to avoid capturing structures on the diffused light coming from the LCD panel. We measured the ramps for red, green and blue channels of the LCD setting the DLP channels to their maximum values. Fifty-two measurements were performed for each of LCD panel and DLP channels from digital level 0 to 255 in intervals of 5 units. The data captured for both LCD panel and DLP were later interpolated to have the spectral radiance for all 256 levels.

We also generated 100 sextuplets randomly as a verification set for the forward model. This random set was built in order to comprise 20 sextuplets that have DLP digital values above the threshold to activate white channel. We measured the XYZ tristimulus values of the random colors displayed on LCD with the same set-up as the LCD panel red, green and blue ramps measurement.

An additional verification set with 280 colors was generated to test the inverse transformation. It consisted of a collection of 14 spectrally flat neutrals that results in luminance values that span most of the measurable dynamic range of the display* from 0.5 to 1300 cad/m^2, 4 octaves of 24 colors of the GretagMacbeth ColorChecker generated from its measured spectral reflectances and finally 170 object colors from Vrhel database.[7] All colors were rendered and evaluated using 2 degree observer and CIE D65 standard illuminant. XYZ tristimulus values were also taken with the spectral measurements and the luminance for the white was used to determine the coefficient K in the colorimetric calculations shown above.

3. RESULTS AND DISCUSSIONS

Figure 1 shows the comparison between XYZ tristimulus values using derived forward model and measurements for 100 random colors.



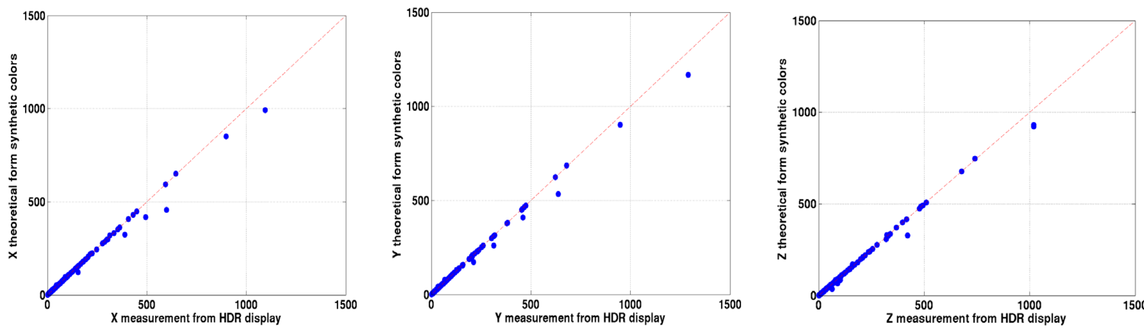
a) X values   b) Y values   c) Z values

Figure 1: Comparison between estimated XYZ tristimulus values using derived forward model against measurements for 100 random colors.

* Effectively our HDR display system presented a dynamic range of 14 bits but in order to be conservative in the low light measurement our verification measurement range comprised only 11 bits.

It is possible to see that the estimated XYZ tristimulus values correlated well with measured values, except for five outliers shown as green stars in which the model estimation underpredicted tristimulus values. Those colors correspond to bright and saturated yellow and orange colors. It shows that our model is inaccurate in this region of color space. The average and maximum CIEDE2000 was respectively 2.1 and 11.6.

Figure 2 shows the correlation between estimated XYZ tristimulus values and measured XYZ values when the estimated sextuplets from inverse transformations were displayed on HDR display. It is possible to observe from Figure 2 that most of the measured XYZ tristimulus values matched well with the original XYZs. Not surprisingly, there were mismatches for the yellow, orange and orange-yellow colors from the brightest octave of the color checker that were underpredicted because these correspond to the color region in which the forward model had accuracy problems besides the fact that some of these colors are also out-of-gamut of this HDR display. There were also two XYZ tristimulus values corresponding to the brightest color checker white and brightest neutral that were also underpredicted. We discovered that our refinement search finds local minima for those very bright colors. Further optimization procedures may overcome this problem. Excluding 7 of these outliers, the CIEDE2000 was respectively 2.4 and 7.7 for average and maximum values.



a) X values b) Y values c) Z values

Figure 2: Comparison between theoretical and measured XYZ tristimulus values from sextuplets obtained by inverse transformation from theoretical XYZ values.

4. CONCLUSIONS

It was possible to model a complex HDR display system based on spectral radiance measurements. Although the HDR display forward model is reasonably accurate for most of tested colors, it is still necessary to perform further refinement for very bright orange and yellow colors. An inverse transformation was proposed and it performed well except for out-of-gamut colors, as expected, and for very bright colors. Further refinements could be performed for these models but we hope these models are sufficiently accurate to be useful in the rendering of HDR images on a HDR display that is compared to a normal dynamic range display, in order to test HDR image rendering algorithms.[8]

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