Display Gamut Reshaping for Color Emulation and Balancing

Abstract

Emerging next generation digital light projectors are using multiple LED/laser sources instead of one white lamp. This results in a color gamut much larger than any existing display or capture device. Though advantageous in theory, when used to display contents captured/processed at a smaller gamut, a large gamut expansion *results in hue-shift artifacts.*

We present a hardware-assisted 3D gamut reshaping method that handles the gamut expansion in LED based DLP displays by hierarchical temporal multiplexing of the multiple primaries. This, in turn, results in a color emulation *technique by which projectors with such large gamuts can also achieve a standard color gamut and white point – the two most important color properties in terms of display quality, with an additional advantage of increased brightness and dynamic range. The same method can also be used for* color balancing *across multiple projectors that are often used to create large-scale high resolution displays.*

1. Introduction

The traditional digital light projection (DLP) technology includes a white light bulb and a color wheel with differently colored filters. The filters are temporally multiplexed at a high speed to selectively pass any one of the multiple primaries at any instant of time on to the digital micromirror device (DMD) array [34]. The number of filters on the color wheel can be three (R,G and B), four (R,G, B and W) or more [30, 13, 24, 1, 25, 6, 15](Figure 1). These are wide band filters creating a gamut smaller than the standard industry-specified gamuts like NTSC, PAL and HDTV (Figure 2). Hence, media in one of these standard gamuts is mapped to the smaller gamut of the display.

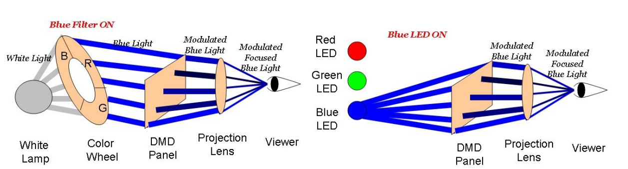

Figure 1. Left to right: Light Path of a traditional DLP projector and a DLP projector with multiple LED sources (Blue filter is ON).

The projection industry has recently introduced projectors where the color wheel is eliminated by using multiple light sources, one for each primary, created from one or more light emitting diodes (LEDs) [8, 29, 10]. The primaries are then switched ON and OFF or multiplexed temporally independent of each other (Figure 1).

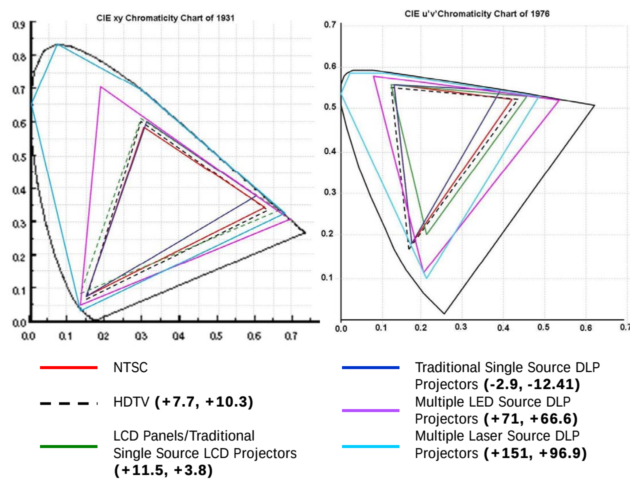

Figure 2. Comparison of the different standard 2D color gamuts with the gamuts provided by the LED or laser based projectors, both in CIE xy and u'v' space. The bold numbers indicate the percentage deviation in the area of the 2D gamut when compared to the NTSC gamut, both in CIE xy and u'v' space respectively

The LEDs in these projectors provide more saturated colors than the color wheel resulting in a much *larger color gamut* than any traditional projector and standard color gamuts like NTSC, PAL, and even the most recent HDTV (56% larger in the CIE u'v' chromaticity chart). In fact, the emerging laser projectors, due to monochromatic primaries, promise to provide an even larger color gamut, covering almost all the colors visible to the human eye (almost double than that of the NTSC gamut in the CIE u'v' space) [20]. The percentage increase/decrease of different display gamuts when compared to the NTSC gamut both in the CIE xy and u'v' chromaticity charts is quantified in Figure 2.

Though larger color gamut assures reproducibility of a larger range of chrominance, this causes *gamut expansion* creating several problems (e.g. hue-shifts, white-point shift and non-optimal utilization of color resources) when displaying existing media generated in devices with a much smaller gamut(Section 3). As a result, these upcoming projectors cannot be used in applications using projectors and cameras in a tightly coupled feedback loop

[18, 17, 21, 37, 19, 35, 28]. When the projected images are captured by the lower gamut cameras severe gamut clipping artifacts occur.

In this paper, we present an algorithm to address this gamut expansion. Unlike traditional single source projector architecture where at any particular instance of time only one of the primaries can be turned on, in projectors with multiple LED sources more than one primary can be turned on at the same time. Our method takes advantage of this key property of *simultaneous ON times* to design a *hardware assisted scheme of hierarchical temporal multiplexing* of the LED primaries that can emulate a standard color gamut and white point without compromising other properties like brightness, contrast and light efficacy, and enables the following.

1. Dynamic Color Emulation: Operability at standard color gamut (like HDTV, NTSC and PAL) and white point (like D85 and D65) is very important for any display. Our method *emulates* many different color gamut and white point standards from the *same* set of LED primaries *dynamically* as demanded by the application, just by changing the parameters of the temporal multiplexing (Section 4). These parameters can be precomputed automatically and then stored in the projector itself.

2. Robustness to Manufacturing Imprecision: The only way to achieve a desired color specification in a traditional single source projector is to control the color properties of their color filters via precision manufacturing. Since our method can achieve the same standard color properties from LEDs that have a large variation in color, such strict control in manufacturing can be avoided. This can make the technology more flexible and cost effective.

3. Color Balancing in Multi-Projector Displays: Finally, the same hierarchical scheme can also be used to achieve color balancing across multiple projectors, common for building large-area high-resolution displays (Section 4.2).

2. Notation

We first briefly describe our color notation. Our algorithm involves only *color matching* and does not deal with color distances. Hence, all computations in our algorithm are carried on in CIE XYZ space. However, when evaluating the display quality, we use a perceptually uniform color space, like CIELAB or CIELUV space.

Let (X, Y, Z) be the 3D coordinates of a color in the CIE XYZ space, called the tristimulus values. In our algorithmic computations, total tristimulus value (TTV) $X+Y+Z$ (the indicator of the total energy of the spectrum) plays an important role. Hence, we specify the (X, Y, Z) color alternatively by its TTV $I = X + Y + Z$, and its chromaticity coordinates (the indicator of its *chrominance*), (x, y), defined as

$$(x, y) = (\frac{X}{X+Y+Z}, \frac{Y}{X+Y+Z}). \qquad (1)$$

The XYZ coordinates of a color can be derived easily from (I, x, y) using

$$(X, Y, Z) = (xI, yI, I(1 - x - y)). \qquad (2)$$

Further, matching two colors, $(I_1, x_1, y_1) = (I_2, x_2, y_2)$ assures that they also match in their XYZ coordinates i.e. $(X_1, Y_1, Z_1) = (X_2, Y_2, Z_2)$. Finally, the most important point to note is that, for colors of similar chrominance, I scales proportionally to the luminance Y. Hence, in displays, for considering each primary or the grays, *I and Y are both scaled equally when the inputs are scaled.*

It can be shown that in the CIE XYZ space, a ray through the origin is the locus of colors with the same chromaticity coordinate (x, y) but different TTVs I. The chromaticity coordinates (x, y) is a 2D projection of these rays on the $X + Y + Z = d$ plane. The set of all chrominance visible to the human eye creates a horse-shoe shaped plot in the xy space that represents different chrominance values phasing out the I. This is called the chromaticity chart (Figure 2). The point $(0.33, 0.33)$ in this chart indicates a perfect achromatic color with $X = Y = Z$. As the colors move away radially from this point towards the periphery of the horse-shoe shape, they change in saturation, while the hue remains constant.

Finally, it can be shown with simple algebra, that adding two colors, (I_1, x_1, y_1) and (I_2, x_2, y_2), result in a color (I_3, x_3, y_3) where I_3 is the sum of the TTVs of the superimposing colors and chrominance is the weighted convex combination of the chrominance of the superimposing colors in the xy chromaticity chart, where the weights are given by the proportion of their TTVs. In other words,

$$(I_3, x_3, y_3) = \left(I_1 + I_2, \frac{x_1 I_1 + x_2 I_2}{I_1 + I_2}, \frac{y_1 I_1 + y_2 I_2}{I_1 + I_2} \right). \qquad (3)$$

This result can be generalized to n colors, where the chrominance of the new color lies within the convex hull of the chrominance of the constituting n colors. Thus, in a projector with three primaries, the reproducible chrominance lies within the triangle spanned by the chrominance of the three primaries (Figure 2). This is called the *2D color gamut* or simply the *color gamut*. The chrominance of the white created by full intensity primaries superimposed from three channels is called the *white point*. This depends on the proportion of the TTVs of the three primaries and need not be the perfect white, $(0.33, 0.33)$. The *brightness* of a device is defined by the luminance Y of full intensity white, and is proportional to its TTV. Note that the white point and 2D color gamut specifies the chrominance capabilities while brightness specifies the dynamic range capabilities. If the brightness of black is constant, a higher brightness indicates a higher dynamic range. When considering brightness and chrominance together, the XYZ values of the primaries

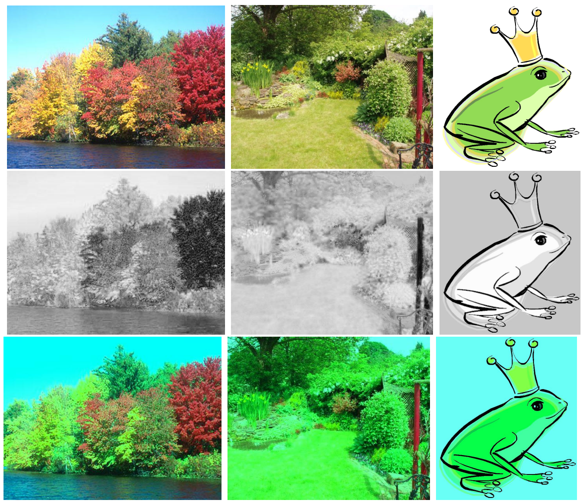

Figure 3. Effects of No Color Management – Row 1: Images in NTSC color gamut; Row 2: The grayscale representation of normalized hue shift in the perceptually uniform CIELAB space due to gamut expansion in LED projectors (Brighter grays indicate more hue-shift) – the normalization is with respect to the maximum hue shift seen in each image; the max and mean hue shift in the three images from left to right are (52.5, 32.8), (55.2, 39.1) and (54.3, 41.8) respectively; Row 3: The images displayed on the LED projector with a larger 2D color gamut is then recaptured by a standard NTSC camera. Note that due to shifting of colors outside of the NTSC space during display, the recaptured image loses many of the colors due to gamut clipping.

span a 3D parellelopipped in the CIE XYZ space. This constitutes the range of all different colors (both chrominance and brightness) that can be reproduced by the device, called the *3D color gamut*.

3. Gamut Expansion and Related Work

A smaller gamut media displayed on a larger gamut display without applying any color management techniques (i.e., no modification of content) can show visible *color incoherence* (jarring hue-shifts) due to the increase in the perceptual distance between two perceptually coherent colors. Figure 3 visualizes this hue-shift at every pixel in perceptually uniform CIELAB space as a gray scale image normalized with respect to its maximum hue-shift in the image (since this cannot be captured or printed in a device with a smaller gamut than the LED projector). Since a hue-shift of 3-5 in CIELAB space is easily visible [38], the hue-shifts resulting from the gamut expansion (between 30-55) is very significant. Note that the color shifts are predominantly in the red-yellow (fall image) and green-yellow (garden image) region of the chromaticity chart where most of the gamut expansion occurs (Figure 2). It also causes a significant *white point shift* (e.g. frog image). A NTSC gamut with standard D65 white (chromaticity coordinate of $(0.3127, 0.3290)$) shifts considerably to the greenish-blue white region $(0.272, 0.369)$ when used for the larger gamut, display. Hence, in any projector camera application [18, 17, 21, 37, 19, 35, 28, 22] when images of the gamut expanded media on an LED projector is captured by a lower gamut camera, gamut clipping results in severe color blotches (Figure 3).

Gamut expansion is prevalent in a much smaller scale when moving from the smaller color gamut of a printer to a larger gamut of a monitor, but not as pronounced as in the context of projection-based displays, especially when using multiple primaries [15, 20]. However, a similar scenario is prevalent currently in the context of dynamic range of displays [27] and has led to development of inverse tone mapping methods that map LDR content to HDR displays [23, 2]. Gamut being a 2D/3D entity, as opposed to 1D dynamic range, makes gamut expansion a more complex problem. In this section, we briefly visit the relevant works in this direction.

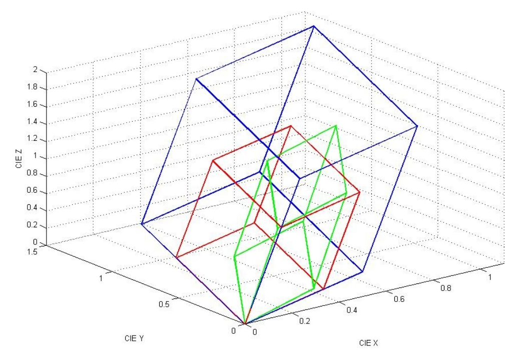

Figure 4. Comparisons of the 3D gamuts in CIE XYZ space of a traditional projector (green) and a LED projector assuming their primaries have the same TTV (red), and 1.5 times the TTV (blue).

Gamut Clipping: Standard gamut clipping techniques [33, 7, 14, 5] are currently used when converting between gamuts of similar shape and volume. The source input $0 \leq (r, g, b) \leq 1$ is mapped to a target color (r', g', b') using a linear transformation M, i,e. $(r', g', b')^T = M(r, g, b)^T$. The resulting (r', g', b'), if outside the target 3D gamut is clipped to the boundary of the 3D gamut. However, this can have some adverse effects on gamut expansion. First, a larger 2D color gamut of the LED projector does not necessarily indicate a larger 3D color gamut. If the luminance (and hence the TTVs) of the primaries are similar, the standard NTSC 3D gamuts may be significantly different in shape and not contained within the LED projector's 3D gamut (Figure 4). Hence, clipping of transformed colors still maps multiple source colors to a single target color resulting in *color blotches* (Figure 3 bottom row).

Gamut Extension: Instead of clipping only the out-of-gamut colors, other techniques aim at moving all different colors in an optimized fashion from the smaller source gamut to the larger target gamut. [12, 26] apply hue-preserving color extrapolation by changing only the brightness (and hence TTVs) and saturation, and [15, 9] apply complex non-linear optimizations on perceptually uniform 3D color spaces constraining the movement of colors within an acceptable distance. However, since the increase in gamut volume in LED projectors is much more drastic than what is expected in these methods, they result in perceivable hue shift [15] and may not utilize the entire gamut.

Comparison of Proposed Method: Our method is complementary to all the above methods. In contrast to complex gamut extension techniques [12, 5, 14, 15, 26, 9], the biggest advantage of our method lies in its sheer simplicity - both in concept and in computation. Unlike existing gamut extension techniques our method can be directly implemented using the existing DLP hardware. Further, our method can exactly emulate a predefined 2D gamut or white point, without working within the confines of the 3D gamut provided by an optimization. Finally, the hierarchical nature of our method (Section 4.1.3) allows a larger flexibility in terms of the emulated properties and extension to multi-projector displays (Section 4.2).

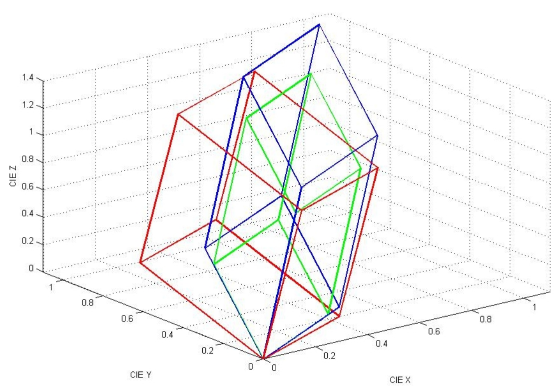

Figure 5. The 3D NTSC gamut (green), 3D gamut of the LED projector before our method is applied (red) and the reshaped 3D gamut of the projector after our method is applied (blue), in CIEXYZ space. The projection of the three basis vectors that span the 3D gamut on a X+Y+Z=d plane is the 2D color gamut. Note that after applying our method, the basis vectors of the reshaped 3D gamut is coincident with the NTSC gamut but is bigger. This assures that the extra 3D volume is used to increase the brightness (and hence the dynamic range), rather than the 2D gamut.

4. Hardware Assisted Gamut Reshaping

Most of the extra volume of the 3D gamut of LED projectors (Figure 4) is used to reproduce a larger range of chrominance, while the range of reproducible brightness, given by the proportional TTVs, is still similar. We present a content-independent hardware-assisted algorithm that *reshapes* this 3D gamut using hierarchical temporal multiplexing, so that most of this extra volume is instead utilized to increase the brightness, while the 2D color gamut is matched to a standard 2D color gamut (Figure 5).

Our algorithm uses this property of *simultaneous ON time* of the primaries to design a scheme to superimpose the multiple primaries in a controlled, deterministic (non-iterative) manner so that any specified 2D color gamut and white point that lies within the gamut can be achieved.

4.1. Color Emulation for a Single Projector

Our method takes two sets of *inputs* – (a) the target (desired) color specifications, i.e., chromaticities of the primaries and white point; (b) the chromaticity coordinates and the TTV, (I, x, y), of the LED primaries at full intensity, measured by a radiometer. The *output* is the pulse width modulated ON-times for superimposing the primaries to achieve the target specifications. Note that this is applicable even to systems with more than three primaries.

Let the measured color properties of the LED primary l, $l \in \{R, G, B\}$, be (I_l, C_l) where $C_l = (x_l, y_l)$ is the chromaticity coordinate of l. Let the target 2D color gamut be defined by the new primaries R', G' and B' whose chromaticity coordinates are $C_{l'}$, $l' \in \{R', G', B'\}$ and the white point chrominance is $C_{W'} = (x_{W'}, y_{W'})$.

The output of the different intensity levels in LED-based DLP projectors are achieved via temporal multiplexing of the ON times of each LED primaries, R, G and B [11]. This forms the Level 0 of our hierarchical scheme. Each of the successive levels run two methods: (a) *temporal-modulation* that determines the relative ON times of the different LEDs which will be turned ON simultaneously to achieve the target specification; (b) *TTV-computation* that determines the TTV of the new primaries thus formed by the temporal modulation step. Figure 6 illustrates the method.

4.1.1 Gamut Emulation in Level 1

The goal of this step is to superimpose the colors from more than one LED to transform the larger 2D gamut to the smaller standard 2D gamut like NTSC (Figure 2).

Temporal Modulation: We control the ON times of the three LEDs to realize the proportions of the LED primaries that achieve the target primaries. t_{ij}, denotes the ON-time for LED primary i, $i \in \{R, G, B\}$, required to create the target primary j, $j \in \{R', G', B'\}$. For e.g. $t_{GR'}$ denotes the ON-time of the green LED primary to create the target red primary.

First, we compute a 3×3 matrix that transforms the triangle $C_R C_G C_B$ to $C_{R'} C_{G'} C_{B'}$, given by

$$\begin{pmatrix} C_{R'} \\ C_{G'} \\ C_{B'} \end{pmatrix} = \begin{pmatrix} d_{R'} & e_{R'} & f_{R'} \\ d_{G'} & e_{G'} & f_{G'} \\ d_{B'} & e_{B'} & f_{B'} \end{pmatrix} \begin{pmatrix} C_R \\ C_G \\ C_B \end{pmatrix} \qquad (4)$$

where $d_{l'}, e_{l'}, f_{l'}$ denote the proportion of R,G and B (barycentric coodinates) required to create the target primaries $l', l' \in \{R', G', B'\}$. Since $f_{l'} = 1 - d_{l'} - e_{l'}$, there are only six unknowns which are provided by the known C_l and $C_{l'}$.

For $I_R = I_G = I_B$, $d_{l'}$, $e_{l'}$ and $f_{l'}$ can be directly assigned to $t_{Rl'}$, $t_{Gl'}$ and $t_{Bl'}$ respectively. However, since

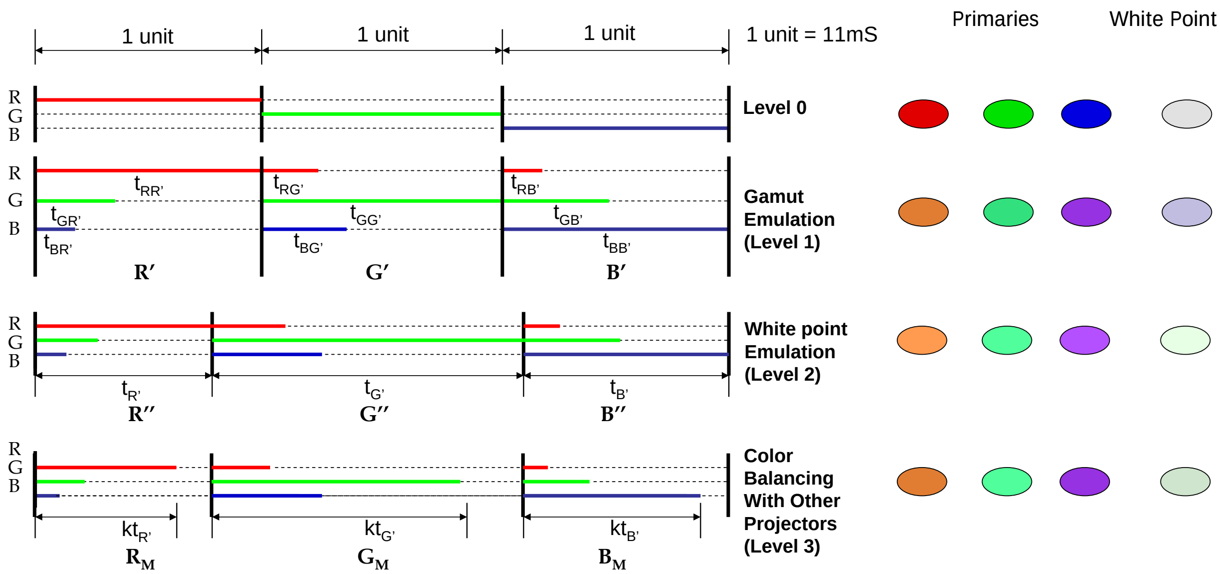

Figure 6. This shows the 33mS time interval for displaying a single frame of a 30fps video. The colored bars show how much time each of the primaries are ON in each interval for each level of the hierarchy. The circles on the right hand side show how the color properties of the display changes with each level. Note that this is just an illustration of the computation and does not correspond to any real data.

$I_R \neq I_G \neq I_B$ in reality, the ON times $t_{Rl'}$, $t_{Gl'}$ and $t_{Bl'}$ required to achieve the target chrominance $C_{l'}$ must take this into consideration. For example, if $I_R < I_G$, then I_R should be kept ON longer to provide the desired TTV proportional to $d_{l'}$. Thus, the timing is a function of both the chrominance and TTV of the source LED primaries. For example, the $t_{lR'}, l \in \{R, G, B\}$ is given by

$$t_{RR'} = d_{R'} \times \frac{I_R + I_G + I_B}{I_R} \quad (5)$$

$$t_{GR'} = e_{R'} \times \frac{I_R + I_G + I_B}{I_G} \quad (6)$$

$$t_{BR'} = f_{R'} \times \frac{I_R + I_G + I_B}{I_B} \quad (7)$$

Since, R' is formed by the superposition of all three of R,G and B, these timings are normalized by the *maximum* of $t_{RR'}, t_{GR'}$ and $t_{BR'}$. For simplicity, we retain the same notation for the normalized timings. Similar computations are performed to compute the timings for G' and B'. For generating $C_{R'}, t_{RR'}$ will usually be much larger than $t_{GR'}$ and $t_{BR'}$ since $C_{R'}$ is much closer to C_R than to C_G and C_B. Hence, for $C_{R'}$, $t_{RR'} = 1$ after normalization. Similarly, after normalization, $t_{GG'} = 1$ and $t_{BB'} = 1$ for $C_{G'}$ and $C_{B'}$ respectively.

TTV Computation: The temporal modulation creates new primaries R', G' and B' whose TTV we compute next. The TTV of the new primary $l' \in \{R', G', B'\}$, is $I_{l'}$ and is given by

$$I_{l'} = t_{Rl'} I_R + t_{Gl'} I_G + t_{Bl'} I_B \quad (8)$$

Since $t_{Rl'} = 1$, $I_{l'} > I_l$. Thus, the new primaries are brighter (due to superimposition of additional light from other primaries) leading to a brighter projector.

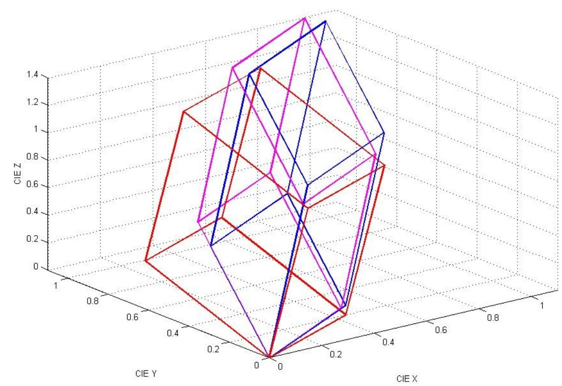

Figure 7. The 3D gamut in CIEXYZ space at Level 0 (red), Level 1 (magenta) and Level 2 (blue) of our method.

4.1.2 White Point Emulation in Level 2

This step realizes the target white point without affecting the new primaries achieved in the previous level using the same steps of *temporal modulation* and *TTV computation* but with the new primaries R', G' and B'.

Temporal Modulation: We modify the contributing proportions of the new primaries, R', G' and B', in such a manner that the chromaticity of target white point, $C_{W'}$, is matched. Let this target proportion be $p_{R'} : p_{G'} : p_{B'}$ where $p_{B'} = 1 - p_{R'} - p_{G'}$. The equation is given by

$$p_{R'}(x_{R'}, y_{R'}) + p_{G'}(x_{G'}, y_{G'}) + p_{B'}(x_{B'}, y_{B'}) = (x_{W'}, y_{W'}). \quad (9)$$

Thus, the ON times for the new primaries to achieve the

Desired Gamut/ White Point	Increase in CIE Y		Decrease in Volume of 3D Gamut	
	Lvl 1	Lvl 2	Lvl 1	Lvl 2
HDTV/D65 (USA)	20.8%	17.1%	3.0%	5.5%
HDTV/D85 (Japan/Korea)	20.8%	19.1%	3.0%	11.1%
NTSC/D65 (USA)	23.4%	20.1%	4.4%	7.2%
NTSC/D85 (Japan/Korea)	23.1%	21.8%	4.4%	13.8%
PAL/D65 (Europe/India)	20.1%	15.9%	2.8%	5.5%

Table 1. Statistics of how the brightness and volume of the 3D gamut of the projector changes in Level 1 and Level 2 from its original state in Level 0.

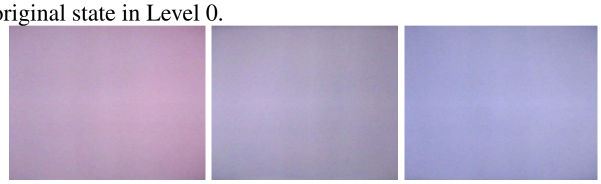

Figure 8. This figure demonstrates the white point emulation. The original non-standard reddish white (0.35,0.325) in CIE xy space (left) has been changed to a neutral D65 white (middle) and a bluish D85 white (right) using our white emulation.

target white point is

$$t_{l'} = p_{l'} \times \frac{\sum_{l' \in \{R',G',B'\}} I_{l'}}{I_{l'}} \quad (10)$$

In this step, the normalization of the timings is different. Unlike Level 1 where the LED primaries R, G and B were superimposed, in Level 2 the primaries R', G' and B' are lighted sequentially for a total of 3 units of time. Hence, $t_{l'}$ should be normalized by $\frac{t_{R'}+t_{G'}+t_{B'}}{3}$. Here also, we retain the same notation for the normalized timings for simplicity.

TTV Computation: Hence, the TTV of the new primaries is given by $t_{l'} I_{l'}$. The TTV of the white, $I_{W'}$, is the sum of the TTVs of these new primaries $I_{W'} = \sum_{l' \in \{R',G',B'\}} t_{l'} I_{l'}$. $I_{W'}$ is proportional to the luminance of the white which is the measure of the display brightness. In Section 4.1.3, we show that $I_{W'}$ is greater than $I_W = I_R + I_G + I_B$ in the original projector.

4.1.3 Discussion

This section offers some useful insights to the transformations achieved by our method.

Reshaping of the 3D Gamut: Figure 7 shows how the 3D gamut reshaping happens across different levels of our hierarchical scheme. The 3D gamut reduces in volume from Level 1 to 2 due to the constraints imposed by a specific target white point. However, the final 3D gamut is always bigger than the standard industry specfied 3D color gamut but smaller than the original LED 3D gamut.

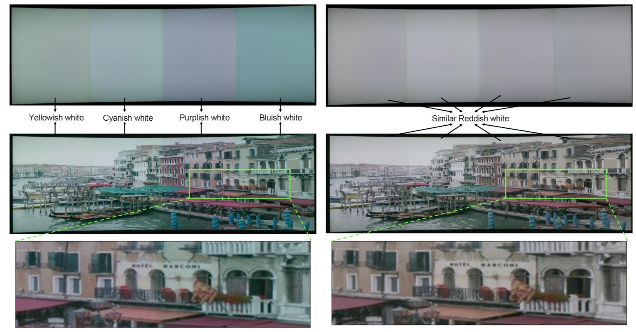

Figure 9. Please zoom in to see our curved screen display made of four projectors (real system, not simulated) running our color balancing algorithm. Top: This shows the whites before (left) and after (right) our color emulation matching to an NTSC gamut. Note that the brightness balancing across projectors described in Section 4.2 is still not applied. Hence, intensity variation and seams are still visible. Middle: This shows a regular content (Venice) before (left) and after (right) our color emulation for each projector to match the NTSC gamut, followed by our TTV (and hence brightness) balancing across projectors and finally removing spatial variation in TTV (and hence in brightness) using existing camera-based calibration methods. Bottom: In this zoomed in views, compare the colors of the buildings near the text `Hotel Marconi` to see the effect of our color balancing.

Table 1 compares the volume of the 3D gamut and the TTV of the white ($I_{W'}$), finally achieved by the color emulation method. Note that since for the equi-chrominance grays of a display, I and luminance Y are scaled similarly with the input (Section 2), $I_{W'}$ provides a direct measure of the increase in the display brightness. However, the loss in the volume is very small when compared to the gain in brightness, which can be as large as 25%.

Hierarchical Nature of the Scheme: Our method is hierarchical in nature where each level of the hierarchy modifies the primaries which are then used as new primaries in the subsequent level. This provides a few nice properties to our algorithm. (a) *Level Independency:* In each step of the hierarchy, only one property of the display is modified *independently* (e.g. 2D color gamut in Level 1 and white point in Level 2). (b) *Preservation of Lower Level Properties:* A color property standardized at a particular level of the hierarchy is preserved through the subsequent levels. (e.g. changing white point in Level 2 does not change the new primaries R', G' and B'). (c) *Module Invariance:* The same computations are used in each level of the hierarchy but with different inputs to impact different properties.

Flexibility of the Scheme: Note that we can precompute timings to achieve multiple different specifications (for e.g. HDTV and D65 white or NTSC and D85 white) and store them in a look-up-table (LUT) in the projector itself. The application software can then use this to create different color properties as the desired white point or gamut used in devices changes from country to country (from NTSC

Figure 10. This shows our planar display made of 16 projectors (real system, not simulated) after color balancing using the following three steps in succession: (a) color emulation of each projector to NTSC gamut (Section 4); (b) color balancing across projectors (Section 4.2); (c) removal of spatial vignetting effects by existing camera-based registration methods.

in US to PAL in Europe/India, from D65 in US to D85 in Japan/Korea).

4.1.4 Implementation and Results

We tested our color emulation on over 20 different projectors to realize NTSC gamut and D65 color point. The time multiplexing was realized using the DLP chip hardware. Figure 8 shows the results of changing the white point from the existing white point (shifted towards red) to a D65 (neutral) and D85 (shifted towards blue) white. Since, the saturated primaries of the projectors cannot be reproduced either in print or in existing displays, we provide statistical data on the accuracy of the gamut mapping. Our red, green and blue LEDs had mean dominant wavelength of 617nm, 520nm green and 464nm with a variation about 16nm, 8nm and 6nm respectively. We achieved an NTSC gamut for all the projectors up to an absolute error of 10^{-4} in the CIE xy chromaticity chart. Since we are dealing with color matching and not dealing with perceptual distances, use of CIE xy space is justified. All measurements (before and after color emulation) were from the same spot on the projector using a Photo Research 705 Spectrascan spectroradiometer.

4.2. Color Balancing Multiple Projectors

The advent of low-cost LED projectors bring in the potential of building very high-resolution tiled projection-based displays that are both portable and affordable [22, 4, 3]. Currently, color balancing across multiple projectors is achieved via software in two steps: (a) first, a common 3D color gamut contained within the gamut of all the projectors is computed; (b) next, a linear [31, 32] or piecewise linear [36] transformation is used to convert the gamuts of all the projectors to the common gamut. For LED projectors such a gamut mapping leads to degradation in image brightness and contrast.

We can use our hierarchical temporal multiplexing scheme to achieve color balancing across multiple projectors in two steps. (a) First, we use our color emulation method to match all the different projector to the same standard color gamut and white point (Section 4). (b) Next, to balance the still varying brightness we add an extra level to our hierarchical method (Section 4.1).

Let us assume n projectors, with projector i having the TTV for white $I_{W_i'}$ following the first two levels. We seek to match the TTV (and hence brightness) across multiple projectors, such that for any $i, j \in 0, \ldots n-1$, $I_{W_i'} = I_{W_j'}$. First, we choose the minimum TTV of all projectors as the target TTV $I_M = \min_{i \in 0,\ldots n-1} I_{W_i}$. Next the ON period of each of the new primaries of the projector i are scaled by $k_i = \frac{I_M}{I_{W_i'}}$ matching the TTV (and hence brightness) of all projectors to I_M. The new primaries thus formed are denoted by R_M, G_M and B_M. However, since the relative proportions of the primaries are not changed, the 2D color gamut and the white point are unaffected by this step.

Our method can only achieve color and brightness balancing across projectors, but cannot handle the intra-projector spatial variation in brightness (commonly called vignetting effect). For this, existing camera-based brightness calibration methods [16] can be used following our color balancing scheme. Since our hierarchical temporal multiplexing method has already modified the larger projector gamut to be close to that of the camera, using a camera in the feedback loop no longer poses a problem.

4.2.1 Implementation and Results

We have implemented our color balancing technique on two displays – (a) a curved display made of four projectors (Figure 9); and (b) a planar display made of 16 projectors (Figure 10). The whites on the calibrated display in the top row of Figure 9 is only after application of our color emulation method, as described in Section 4. Hence, the brightness variation across projectors and the spatial vignetting is still evident. All the other images of calibrated displays are achieved by applying three steps: (a) color emulation, as in Section 4; (b) brightness balancing as in Section 4.2; and (c) removal of spatial vignetting by applying the methods in [16]. Note that these three steps make both our four and sixteen projector displays perceptually seamless.

5. Conclusion

In conclusion, we demonstrated that the larger gamut of the current LED projectors lead to several hue-shift artifacts and sub-optimal utilization of color resources when displaying existing lower gamut media due to gamut expansion. We presented a content-independent hardware-assisted method that reshapes the 3D gamut to match a standard 2D color gamut while directing the extra volume towards achieving a higher dynamic range. This method can be used for color emulation of single projectors and also for color balancing multiple projectors.

As is evident, in the future it is critical to explore approaches to develop a sensor with large gamut so that the display resources can be utilized to its fullest. One can also explore better content-dependent approaches in the future that can handle very large gamut expansions so that the larger chrominance gamut offered by these emerging displays are optimally utilized.

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