10.2: Wide gamut, high brightness multiple primaries single panel projection displays

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Abstract

The color gamut of RGB primaries displays can be increased by using more saturated primaries, with the penalty of a corresponding significant decrease in brightness. We present a multiple primaries technology that enables substantial increase in both the color gamut and brightness of projection displays and describes results of prototype projection systems using the technology.

1. Introduction

Historically, the color gamut of displays has been constructed from three primary colors – Red, Green and Blue. For CRT displays, the primaries colors are determined by the specific phosphors in use, while for LCD and microdisplay-based projection displays the primaries are determined mainly by the nature of the light source and the spectral transmission of the color filters. For practical reasons, the resulting color gamut of displays was limited to a much smaller gamut than the originally desired NTSC gamut. In some home cinema and wide gamut LCD displays, narrow band transmission filters were used, enabling larger gamut but at the expense of a significant decrease in brightness efficiency. The possible use of laser [1] or LED backlight [2] displays, which are capable of showing a large gamut, is hampered by their high cost, making these solutions unviable for the mass market.

The use of more than three primaries to increase the color gamut of displays beyond the RGB triangle has been demonstrated [3]. However, the suggested implementation has been not viable for commercial mass production displays, due to technological gaps, mostly related to increased cost and reduced brightness efficiency. This may be why multi-primary commercial displays have never been realized.

We have developed a practical multi-primary technology that enables substantial color gamut increase. The color gamut and its utilization are optimized for enhanced viewing experience. The resulting brightness of the wide gamut system is comparable, and in most cases higher, than that of the corresponding conventional “low gamut” display. Alternatively, it is possible to implement our technology to substantially increase display brightness efficiency while keeping the original color gamut. This approach is useful in mobile display or business projection applications.

The multi-primary concepts and algorithms that we have developed can be adopted with low cost modifications on different display technologies, including but not limited to direct view LCD and microdisplay-based rear and front projection.

In this paper we shall discuss in detail the applicability of the technology to single panel microdisplay-based projection displays. Also, we shall present experimental results of our projection display demonstrators.

2. Projection displays

2.1 Analysis

In digital projection displays, images of the primary colors are projected onto a viewing screen, and combine there to create a full color image. In three panel devices each primary color has its own optical channel, while in single panel projectors all primaries share the same optical channel, at different time slots. For mass market applications such as TV or business projectors, cost is a major factor in the display design. Therefore, the lower cost of single panel optical engines makes them the preferred choice for microdisplay-based (LCoS, DLP^{TM}) projection devices.

Since in single panel optical engine design all primaries share the same optical path, these engines are easily modified to support multi primary technology. The optical engine of a single panel multi-primary display is basically similar to that of a three primary display. One obvious difference is the required change in color switching mechanism, e.g. the color wheel or color drum, which must have more color segments. Furthermore, the electronics that drive and control the loading of the data into the panel in phase with the color switching must be modified to enable operation with the desired number of primary colors. Finally, a converter is needed that transforms the available input data (YCbCr or RGB) to the multi-primary format.

The modification of the panel driver and controller is strongly coupled to the specific panel technology in use. Therefore, of the three elements mentioned above, we shall discuss the realization of the color primaries and the converter, which are more general in nature. Nevertheless, it is worth mentioning that the response time of current panel technologies supports the timing requirements of multi-primary technology at the required bit depth. Note that due to the multi-primary effect not all primary colors require the same bit depth, and therefore the effective bit rate is not linearly related to the number of primaries.

2.2 Color primaries for multi-primary projector

The color of the primaries in a projection display is determined by the spectra of the light source, spectral transmission of the optical engine (including the panel response), and the color filters. Of these elements, the color filters have the dominant effect and their design is the most relevant to the color gamut of the display [since the other elements are restricted by other considerations]. We have developed a process that enables optimum filter selection taking into account required performance, i.e. color gamut, required white point, ratios between primaries luminance and white point brightness, and actual system constraints such as the spectra of the light source, the spectral transmission of the optical engine and other optical parameters. The result of this optimization is the filter transmission spectra, their segment size and order (on a sequential color wheel or color drum).

The optimization process starts by choosing a two-dimensional area to be covered in the chromaticity space. For example, this

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area may be the “NTSC triangle”, a typical cinema color space, or any other desired gamut. Various possible filter transmission curves are evaluated that meet the chromaticity requirements. This evaluation takes into account the spectrum of the lamp and the transmission spectrum of the optical engine, as well as the change in the effective transmission of the filters due to divergence of the light passing through them. A few preliminary sets are chosen, and the relative primaries luminance is adjusted by controlling their segment sizes (when applicable). In most cases, the required color filter tolerances will be within the normally accepted commercial products tolerance levels. The white point luminance and its sensitivity to changes in color temperature are evaluated, and the most suitable solution is chosen.

In figure 1 we present examples of the possible color gamut obtained by 4 and 5 primary displays, with white point at D65. For each example, we also calculate the ratio of the luminance of the multi-primary display to that of three-primary RGB optical engines, with Recommendation ITU-R BT.709-3 (Rec. 709) or NTSC primaries. The calculations are done assuming a 100W UHP^{TM} lamp spectra and typical optical engine spectral transmission.

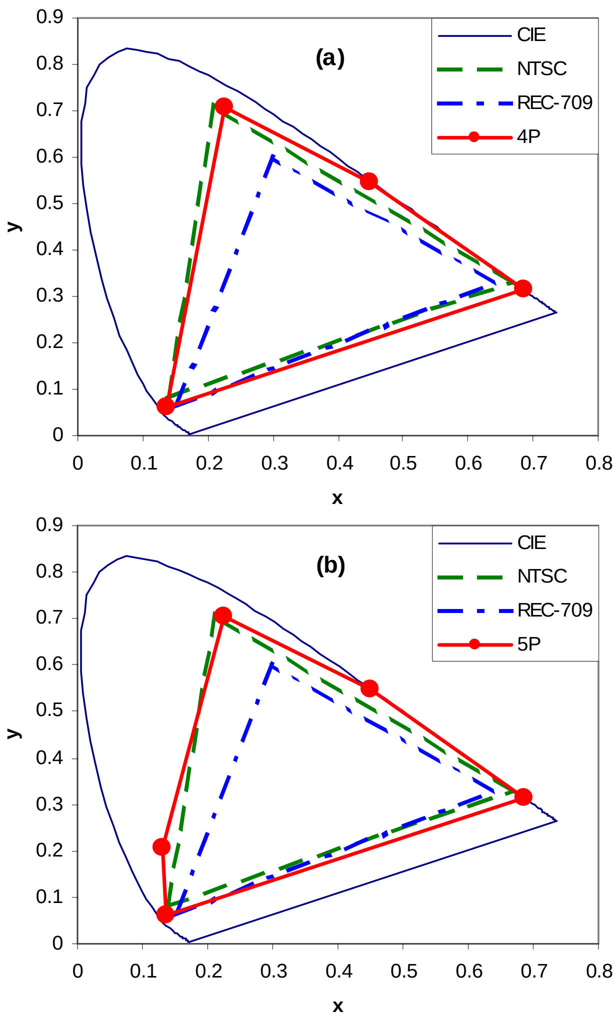

Figure 1: 4 primaries (a) and 5 primaries (b) wide gamut designs

The relative luminance ratios are presented in table 1. Even though the gamut of the multi-primary display is substantially larger than that of the Rec.709 primaries display (and larger even than that of the NTSC primaries display), its luminance is much higher than that of the NTSC primaries display and comparable with that of the smaller Rec.709 gamut display.

The increase in the color gamut is obtained by a selection of the RGB primaries color coordinates and the addition of a yellow primary (and a cyan primary for the 5 primary display). Yellow is known to have high luminance, in particular in the case of projection engines based on the UHP^{TM} lamp, which has a strong yellow line in its emission spectrum. The inclusion of this line in the red and the green primaries of an RGB display would make those primaries unsaturated. Therefore, this line is usually rejected in RGB projectors. In the case of multi-primary engines, the luminance associated with this line is made useful.

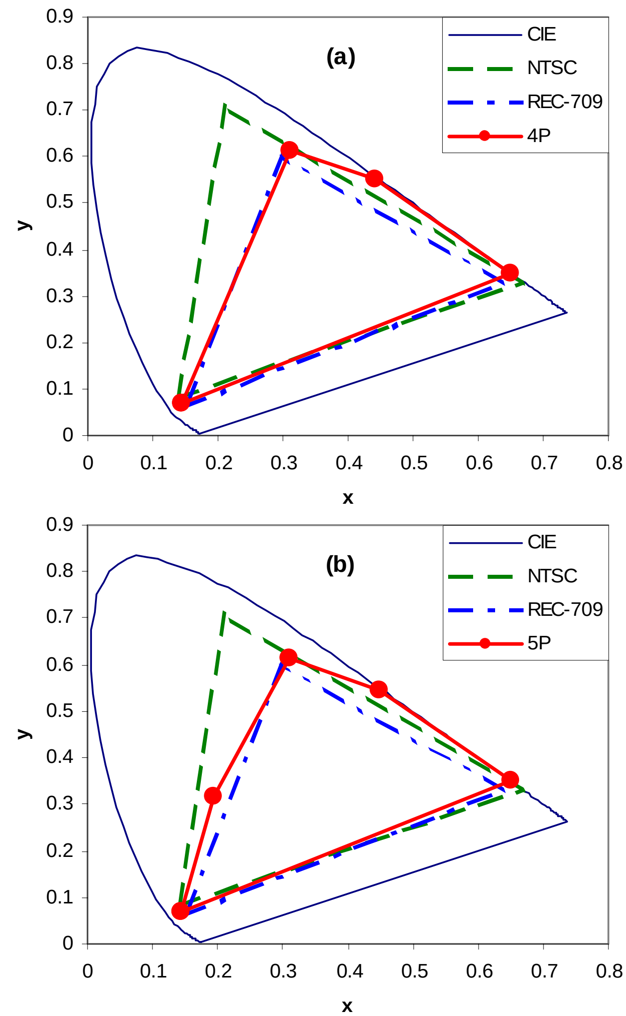

Figure 2: 4 primaries (a) and 5 primaries (b) high brightness designs

For front projection business applications that demand high brightness to permit use with higher levels of ambient light, it is possible to use less saturated colors and achieve a substantial increase in luminance. In figure 2, we present possible designs of 4 and 5 primary displays with “Rec. 709 like” gamut. In these configurations, a brightness gain of up to >40% with respect to the luminance of a Rec. 709 display can be achieved (see table 1). Even though the design is for Rec. 709 gamut, the gamut of the multi primary systems is larger than that of the three-primary display, enabling presentation of saturated yellow, orange and cyan colors.

By proper filter choice and system optimization, many gamut/brightness trade-offs between the examples shown above can be achieved.

Table 1: **Normalized brightness of the different designs**

Display Configuration	Normalized Brightness
3 Primaries, "REC-709"	**1**
3 Primaries, "NTSC"	.54
4 Primaries, wide gamut	1.09
4 Primaries, high brightness	1.43
5 Primaries, wide gamut	1.00
5 Primaries, high brightness	1.39

2.3 The multi-primary converter

The multi-primary display requires multi-primary input; however most existing content is in a three-component format, such as RGB or YCbCr. Therefore, we have developed an algorithm that accepts a three-component input and converts it to a multi-primary format suitable for the display. This algorithmic conversion has several difficulties that do not rise in the three-primaries systems. First, the input RGB or YCbCr data are device-dependent color formats, the translation of which to absolute color is done by the physical RGB primaries of the display. [In the case of YCbCr data, matrix conversion is used to transform the YCbCr into RGB information]. In the case of a multi-primary device, there is no direct relationship between the RGB inputs and the physical primaries. In order to overcome this fact, the input data is processed with respect to a reference color space to obtain XYZ device-independent color representation. Since most data are designed to be presented on standard RGB displays, the gamut of which is very different from that of the multi-primary displays, some "gamut matching" should be applied. The "gamut matching" process ensures that data points which may be outside the gamut of the multi-primary display would be mapped into it. More importantly, it makes use of the extended gamut of the multi-primary display in saturated colors, with respect to the standard RGB gamut. The resulting XYZ color should then be presented on the multi-primary display; this requires finding the coefficients a_i as per:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \sum_{i=1}^{N} a_i \begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix} \quad \text{where} \quad 0 \le a_i \le 1 \quad i = 1..N$$

Here, we assume that the contrast of the display is high so that the contribution of stray light is negligible. [In practice, this is not the case and some correction for that is applied.] The three-component XYZ color does not specify the multi-primary output a_i unambiguously. Therefore, there is a need for choosing a solution between the infinite set of possible solutions [In practice, the number of possible solutions is not infinite because of digitization]. A unique solution is chosen by imposing further constraints on the a_i's. However, the solution of the constrained problem in video speeds is almost impossible. A simple way to overcome this problem is to calculate the a_i's for all possible combinations of input data. However, this requires a large amount of memory, which is expensive on one hand and implies long access time to memory on the other hand. Therefore, we have developed an algorithm that performs the above functionality in real time at video speeds, using a low amount of memory.

Although both RGB and YCbCr inputs are possible, in most cases YCbCr information is preferable. The reason is that the YCbCr color space is much wider than its corresponding RGB color space, in the sense that there are many YCbCr combinations that translate to colors that are not presentable on an RGB device. Furthermore, many of these colors are valid colors that are visible to the human eye. Using Monte-Carlo simulation we compared how well RGB colors represent valid colors and colors within the object-color solid of D65 illuminant. The results are summarized in Table 2.

Table 2: Comparison between different color spaces

	% YCbCr cube	% valid colors	% D65 color solid
Valid colors	85%	100%	
D65 color solid	67%	79%	100%
RGB colors	25%	29%	37%

It can easily be seen from the above table that the RGB colors represent only a small fraction of the valid colors (29%) and the D65 object-color solid (37%). On the other hand, most of the YCbCr color space represents valid colors. The valid colors occupy 85% of the YCbCr color space volume. The D65 color-object stimuli occupy a smaller part, only 67%. Note, however, that in many cases the illumination is not restricted to D65, and thus the volume of possible colors is probably larger. Although not all colors in the D65 object-color solid can be represented in valid YCbCr encoding, these colors are only a small fraction of all possible stimuli.

3. A multi-primary projection display

A schematic block diagram of a digital TV system operating on multi-primary concept is shown in the inset of figure 3. A front-end unit accepts the input data from DVD or DVB, performs the decryption and the MPEG decoding, followed by scaling to the display resolution to obtain a YCbCr (4:4:4) stream that enters the multi-primary converter. The multi-primary converter accepts YCbCr (4:4:4) input and converts it into digital multi-primary signals. These signals are fed into the multi-primary display driver.

We have developed an electronic board that performs the functionality of the multi-primary converter. A schematic block diagram of the board is also shown in figure 3. The video channel accepts YCbCr input and a timing signal on a DVI interface. The algorithm is performed in a firmware loaded in an FPGA, and the multi-primary output of up to six primaries is provided on two single pixel DVI channels or on a dual pixel DVI channel. The converter can accept data up to SXGA (1280*1024), including 720p resolutions, at update rates up to 60 Hz. It can operate in stand-alone mode or in a controlled mode from a PC. Various parameters of the algorithm, and different display configurations may be stored on flash memory and loaded into the video channel via a remote control or via a control line connected to a PC using USB or RS-232. Alternatively, commands and parameters may be transferred from the front end or the panel driver via IC^2 control lines. The MPC can support 8 bits per primary up to six primaries. System configuration and algorithms determine the actual number of primaries and bits required for each primary. This board will be reduced to ASIC in the future.

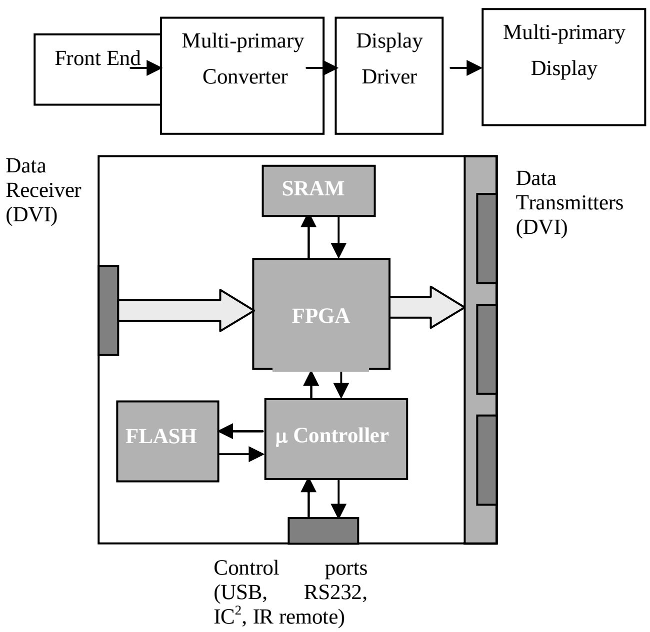

Figure 3: Data flow in digital TV and a schematic block diagram of a multi-primary converter

4. Experimental results

We have constructed several wide gamut demonstrators based on the concept described above, using 4, 5 and 6 primaries. The displays were constructed by superimposing the image of two single panel DLP™ projectors. The color filter wheel in each projector was replaced with a color wheel with identical segment sizes but our designed filters. For 6 primaries we used different filters for each segment. We simulated 4 and 5 primaries by including one or more identical filters on both color wheels.

The actual measured performance of the displays as compared to the designs, was measured. The color coordinates of the primary colors were within error boxes of +/- 0.02 for both the x and y coordinates. The white point deviation from the design was less than 500º K. The white brightness met the design values within an error of approximately 10%.

The displays were compared with high quality, market-leading TV sets, and with front and rear digital projection displays. We found that even for 4 primaries, there is a significant advantage of the multi-primary display over an RGB display. The advantage is most evident in scenes that contain vivid green, yellow, orange and red colors. Adding the fifth primary also significantly enhances the cyan colors that exist in many scenes. The sixth primary may further enhance the viewing experience and give additional degrees of freedom.

We presented our display to focus groups. They were exposed to different scenes, including still pictures, video clips from different movies and live TV broadcasts. All participants unanimously preferred our demonstration display over the reference TVs. It is important to note that in many cases the observers commented that the multi-primary display appears sharper than the standard RGB display, although both have the same resolution. One explanation for this is that the enhanced saturation allows better color resolution. Another might be related to the unconscious correlation between image sharpness and its vividness and colorfulness; foggy or hazy conditions tend to reduce color saturation and at the same time blur details. We suppose that the improved color quality of the multi-primary image unconsciously translates into sharpness, based on the human experience.

5. Conclusion

We have developed a practical method that enables the construction of wide gamut displays with high brightness efficiency. The technology can be implemented in LCD, projection and other display types requiring only low cost modifications. We have built several projection systems with four to six primaries and demonstrated them in both front and rear projection applications. We have developed algorithms for the conversion of the three primaries input data to the required multi-primary input data. The algorithms are implemented on a real time multi-primary converter electronic card.

6. Acknowledgements

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7. References

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