Color Rendering Pipeline of a Color Tunable Reflective Display

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Abstract

A color tunable reflective display (CTRD) is a reflective display in which primary colors are tunable. With the availability of a large amount of high chromatic primaries, it produces much richer colors than other reflective displays. However, due to a large amount of primaries and the lack of intensity depths, a regular display color pipeline cannot be applied. This paper presents a method to enable superior color gamut of the CTRD technology.

Introduction

Reflective displays are more attractive than emissive displays for outdoor usage and for mobile applications where reducing power consumption is critical. Interferometric modulator (IMOD) display is a micro-electro-mechanical system (MEMS) used in electronic visual displays that can create various colors via interference of reflected light. An IMOD-based reflective flat panel display includes hundreds of thousands of individual IMOD elements each a MEMS-based device. It selectively absorbs and/or reflects light using the principles of optical interference and absorption. Similar to other reflective displays, it consumes very little power when display contents are not changed. Yet, it produces much richer colors (i.e. larger color gamut) than other reflective displays. In the first generation of the mirasol display, three primary colors are generated with thee IMOD elements, each may include a pair of conductive plates with a specific air gap to produce a color. By adjusting the position of one plate relative to the other, it changes the optical interference of light incident on the IMOD display element and therefore changes colors. Properly setting the air-gaps of the three IMOD elements, red, green, and blue primary colors are produced. In an adjustable IMOD display, hundreds of primary colors may be produced, thus makes the primary color tunable. Instead of producing red, green and blue primary colors, a tunable display can produce much more primary colors. Fig. 1 shows 256 primaries produced by a tunable display.

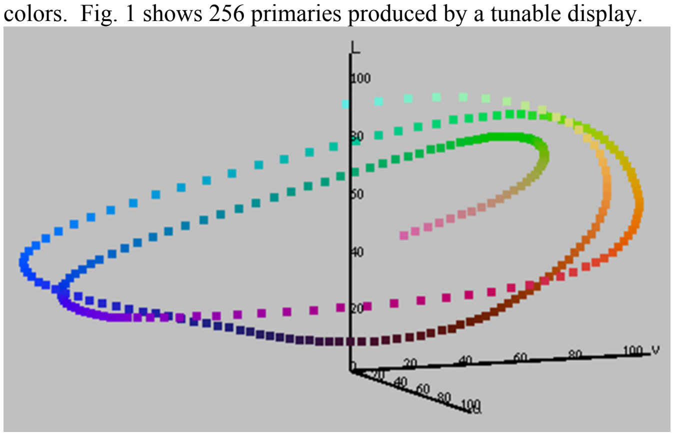

Figure 1. *256 primary colors produced by a CTRD (in CIELUV color space)*

In a reflective display, such as a mirasol display, the intensity of each color cannot be changed under a fixed lighting condition, i.e., the intensities of primaries are binary. Similar to print hardcopy, the intensity may be produced by spatiotemporal modulation. Additionally, each pixel can only produce a primary color at a time. Furthermore, an interferometric modulator mostly produces highly chromatic colors only. With such characteristics, the color processing method of a traditional display cannot be applied. A new color rendering pipeline specifically for this display technology was therefore developed. This paper presents following topics of the color rendering pipeline: 1) the transformation from sRGB to device primaries; 2) primary selections; 3) gamut mapping; and 4) spatiotemporal modulation. Other subjects, such as black primary and white primary optimization and angular metamerism, will be covered in another paper.

Color Transformation

A CTRD produces more primaries than a traditional imaging device. In each pixel position, a primary is produced, i.e., two primaries cannot be produced simultaneously in a pixel location. For example, in an interferometric modulator based display, to make an N-primary display, the pixel is configured to have the air gap changed among N different positions. One difference from a traditional display is that it cannot display two primaries simultaneously. Instead, it produces primaries sequentially. To discuss the difficulty of using a large amount of primaries that can only be fired sequentially, let us compare it with a six-color inkjet printer. To print a three-channel sRGB color, the color is interpolated to six inks, and halftoning is then applied to determine ink nozzles to be fired. If the same workflow is applied to a six-primary reflective display, an sRGB color is transformed into up to six primaries and then displayed. If four sub-frames are available to display each frame of an sRGB color, the color can only be displayed with up to four primaries instead of six primaries. In a P-primary reflective display (the number of primaries is P), each pixel can display one of the P primaries at a time. With F sub-frame modulation (each frame in divided into F sub-frames), a pixel is allowed to tune color F times and produce up to F primary colors. If P is larger than F, the interpolation from sRGB to the device color space must be limited to using F primaries for producing a color. Fig. 2 shows an example of a traditional 3-D interpolation to transform sRGB to a three-primary display, where a 17x17x17 uniform sampling lookup table (LUT) is used. To display an sRGB color, e.g. RGB=(24, 0, 0), two neighbor nodes in the 3-D LUT, sRGB (16, 0, 0) and sRGB (32, 0, 0) are applied to interpolate the color to the display color space, devRGB. Since (24, 0, 0) is exactly in the middle of the two nodes, the interpolation is the average of the two neighbor nodes. A single primary color, sRGB (24, 0, 0), is mapped to a three-primary devRGB color (28, 4, 3) in this example.

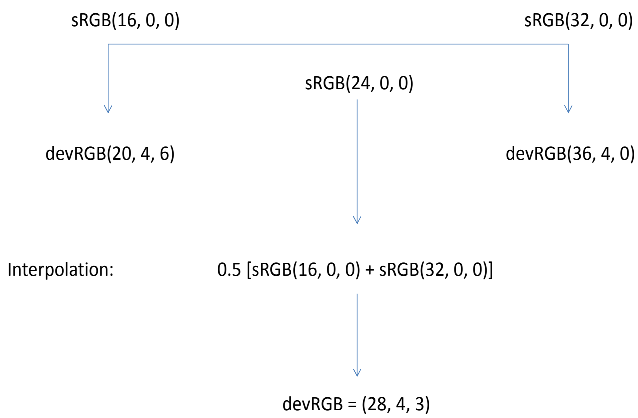

***Figure 2**. A 3-D interpolation example*

If we apply the same interpolation scheme to such multi-primary display, an sRGB color may be interpolated to the display device color that is mixed with many primaries as shown in Fig. 3. An sRGB color is interpolated to six primaries in this case. This requires six sub-frames to mix colors. Since changing each frame contents in reflective display consumes power, high sub-frame modulation may not desirable. Due to the limitation of available sub-frame modulations, this method of transformation may be impracticable.

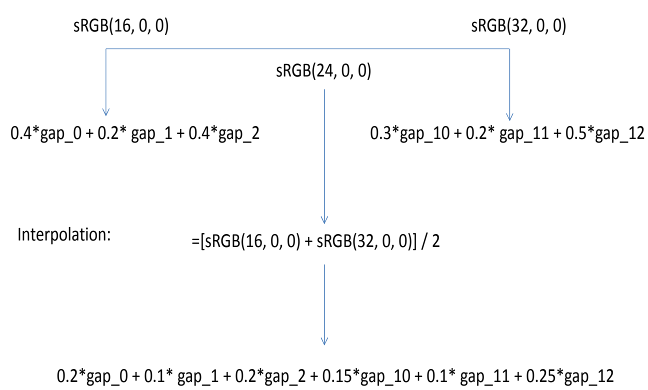

***Figure 3**. Transform an sRGB color to a multi-primary reflective display color using a 3-D interpolation method*

In order to solve the problem, a source color is not directly interpolated to the device color space. Instead, a 3-D LUT is constructed to gamut map the source color space to an intermediate color space, which is a uniform and device-independent color space (e.g. CIELAB, CIELUV, or CIECAM02 JAB). Next, spatiotemporal error diffusion is applied to map colors from the intermediate color space to output primaries (see Fig. 4).

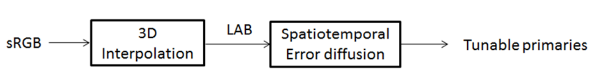

***Figure 4**. A Color rendering workflow for the color transformation used in the CTRD technology*

Primary Optimization

With the limitation of sub-frames, power consumption, precision control of interferometric modulation, and hardware and performance concerns, a subset of primaries are selected for practical applications. In Fig. 1, hue angles of primary colors turn about two rounds. In order to reduce power, we may pick a small set of primaries in a limited air-gap range. Fig. 5 shows a set of 8 selected primaries (black squares) in CIELUV color space (left) and in CIELAB color space (right). By picking one more primary between two neighbor primaries, a set of 14 primaries (black squares and red circles) may be constructed.

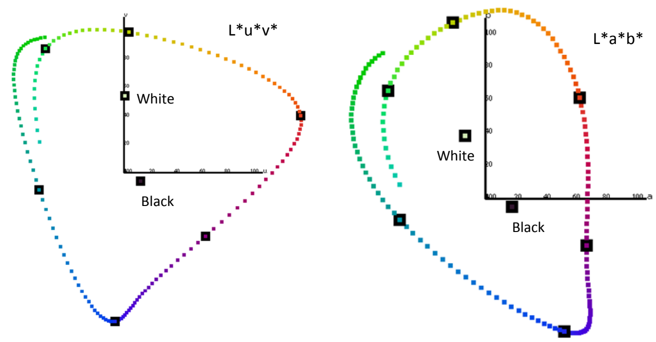

***Figure 5**. Primary reduction for system optimization*

Gamut Mapping

Fig. 6 shows the gamut comparison of a source color space and a CTRD in a typical office viewing condition. Because the shapes of two gamut sets are so different, a soft gamut compression method is performed to map source colors to the CTRD gamut [2]. A 3-D LUT is generated to transform source colors to an intermediate uniform color space for 3-D interpolation as shown in Fig. 4.

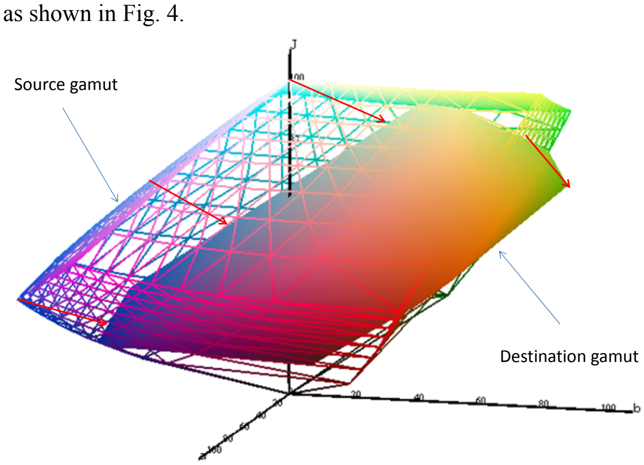

***Figure 6**. Gamut comparison of a source gamut and a CTRD in an office viewing condition.*

Spatiotemporal Modulation

Since a CTRD produces primary colors in fixed intensities, halftoning is applied to create shades of colors. In Fig. 7, the left plot shows a hue slice composed of the black primary, the white primary, and a color primary. Any color within the triangle may be produced through halftoning. In the middle plot, two sub-frames are used for temporal modulation, which is equivalent to producing three extra primaries, named virtual primaries (KP, WP, and WK) in this paper. The triangle is divided into four smaller triangles. Spatial halftoning is then applied to produce colors within each small triangle. It illustrates that temporal modulation significantly reduces error propagation in the next step of spatial halftoning. In the right plot, three sub-frames are used for temporal modulation, and therefore more virtual primaries are produced to construct even smaller triangles. The more sub-frames available, the less the error propagation in spatial halftoning and therefore less halftoning visibilities. If temporal modulation colors (virtual primaries) are considered primaries and pre-computed, the spatiotemporal modulation can be simplified as spatial halftoning and significantly improve the halftoning efficiency. Fig. 8 shows the overall workflow. The 3-D LUT is constructed by gamut mapping the source color gamut to the destination and converting source colors to an intermediate color space. The extended primary LUT in the block diagram are the physical primaries plus virtual primaries. An input color is first transformed to the intermediate color space by 3-D interpolation, and then to the tunable primaries by spatiotemporal modulation or vector error diffusion.

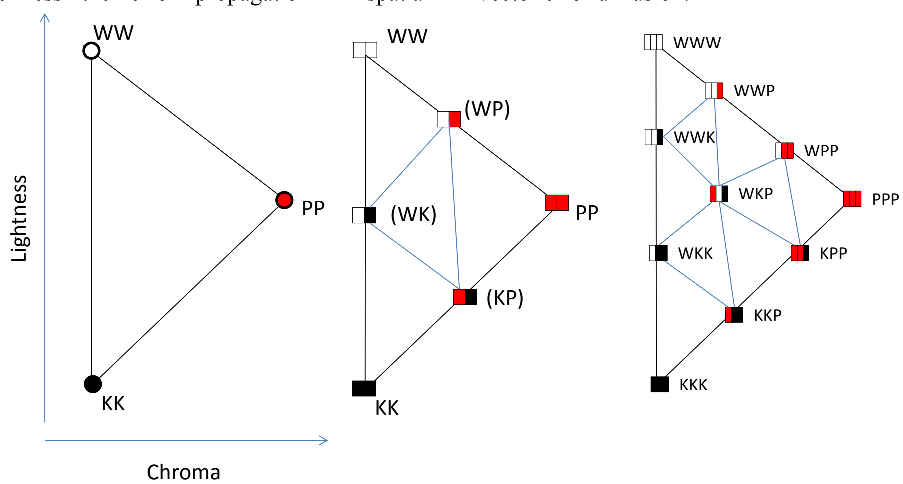

***Figure 7**. Temporal modulation in a hue plane*

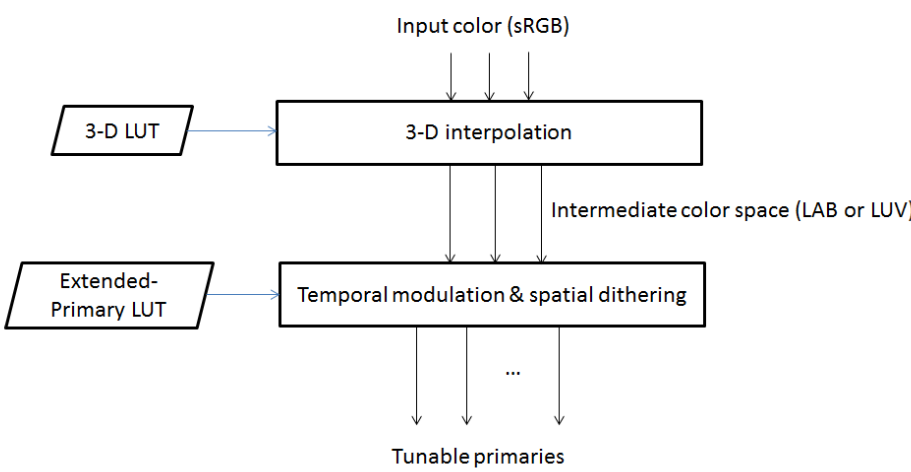

***Figure 8.** CTRD color rendering pipeline*

Simulation

Following parameters were applied for simulation of the CTRD technology: 4-sub-frame modulation for display videos, a fill factor of 80% was considered for complex pixel structures; 64 primaries were chosen. With such configuration, the power consumption was much lower than using LCD/LED displays. Fig. 9 shows a source sRGB image and its relative-colorimetric simulation on a CTRD (64 primaries, 80% fill factor, 4 sub-frames temporal modulation, vector error diffusion, R=G=B normalized to the same brightness) [3-4]. The brightness primary is not a neutral white for perfect non-absorption is not possible. Because the white primary of the reflective display is not neutral, the source sRGB white has to be mapped to the brightest white or a neutral color with lower brightness. In this example, the source white is mapped to the slightly yellowish CTRD white primary.

***Figure 9**. An sRGB image (left) and the simulation on CTRD (right)*

Fig. 10 is a comparison of the simulation between an LCD display and a CTRD display under different ambient lights. The top row is the simulation of sRGB images on an emissive display with maximum white brightness of 200 cd/m^2. The bottom row is the simulation of sRGB images on a CTRD display. 1% flare and 1% surface reflectance are assumed. Ambient light luminance is zero on left and gradually increase to very bright on the right. The brightness of the simulation images on the reflective display is scaled down to fit on LCD displays when ambient light is very bright. The visual contrast and readability on the emissive display decreases as ambient light increases, while the effect on the reflective display is exactly opposite. As ambient light gets brighter and brighter, the contrast and readability on the emissive display eventually diminishes while the contrast and readability on the reflective display gets higher and higher. Under regular ambient light, the reflective display looks darker than emissive display. This can be resolved by applying front-lit lighting if power consumption is not an issue.

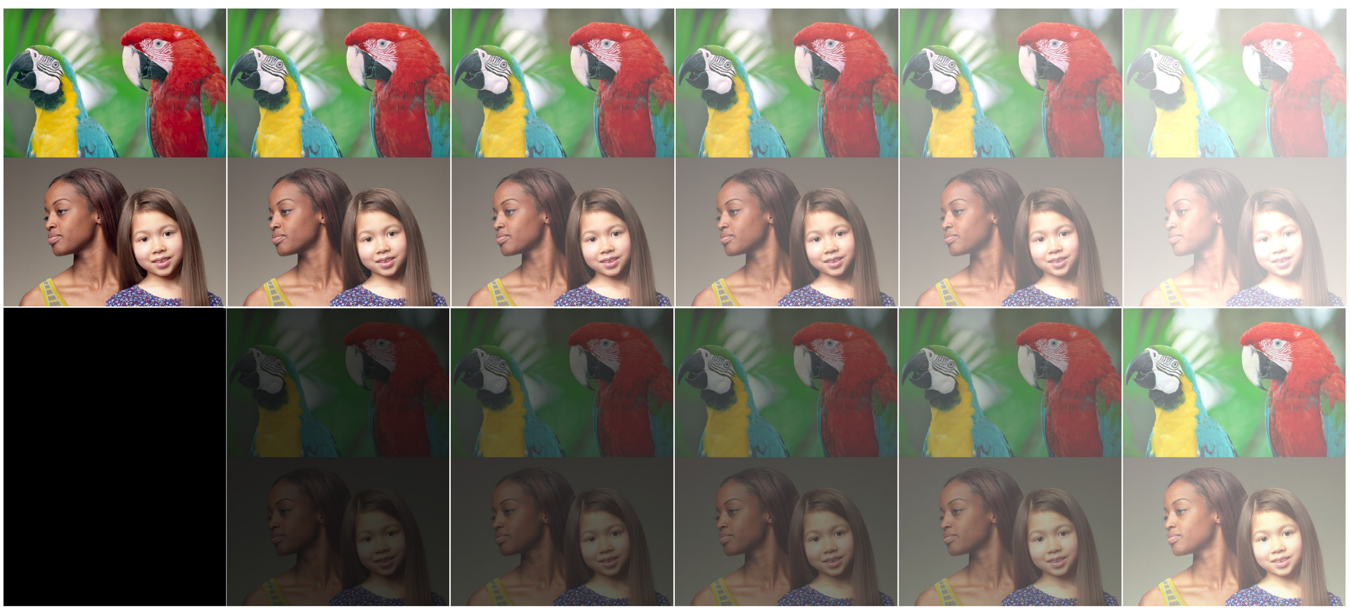

***Figure 10**. Simulation of sRGB images on an emissive display and a color tunable reflective display. Ambient light is zero on the left image and gradually increase to very bright on the right image.*

Conclusions

A color rendering pipeline is developed for the color transformation for the CTRD technology. The simulation reveals that in indoor viewing conditions, the display produces rich colors but images looks darker than that on an emissive display. In outdoor viewing condition, the display produces superior color images that are not available on emissive displays and other reflective displays.

References

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Author Biography

Huanzhao Zeng is senior color imaging scientist at Qualcomm since 2012 developing color imaging technologies for e-reader displays and mobile phone cameras. Before joining Qualcomm, He was a principal color imaging scientist in Imaging and Printing Group, Hewlett-Packard Company for 12 years, working on research and development of high-speed inkjet printing systems, multi-function printers, photo-mini-labs, and commercial printers. He has over 50 publications and over thirty invention disclosures in color imaging field.