POWER-CONSTRAINED RGB-TO-RGBW CONVERSION FOR EMISSIVE DISPLAYS

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ABSTRACT

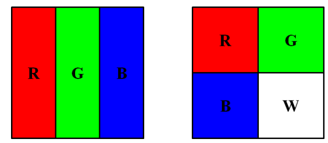
We propose a novel power-constrained RGB-to-RGBW conversion algorithm for emissive RGBW displays. We measure the perceived color distortion using a color difference model in a perceptually uniform color space, and compute the power consumption for displaying an RGBW pixel on an emissive display. The main contribution is to formulate the optimization problem to minimize the color distortion subject to the constraint on the power consumption. Then, we solve it efficiently to convert an image in real time. Simulation results show that the proposed algorithm provides significantly less color distortion than the conventional methods while providing a graceful trade-off with the amount of power consumed.

Index Terms— RGB-to-RGBW conversion, RGBW display, color distortion, and low power image processing.

1. INTRODUCTION

The advancement of digital imaging technology enables a variety of multimedia devices, such as mobile phones, to display high resolution images. As the resolution of an image increases, the density of displays becomes higher in terms of pixels per unit area. However, as this density increases, the light efficiency of a display reduces, since the aperture ratio, which refers to the area ratio of the light transmitting area and the total display area, decreases. One of the recent researches in display technology to increase the light efficiency is to add white (W) subpixels to the conventional RGB display as shown in Fig. 1, which is called the RGBW display [1–3]. However, an RGB-to-RGBW conversion process is needed to use RGBW displays, since display systems typically take RGB images as input [2–4]. Also, the image quality of an RGBW display depends strongly on the RGB-to-RGBW conversion. Therefore, RGB-to-RGBW conversion is an important research topic in the display community, and several algorithms have been proposed for the conversion [2–7].

Another important issue in designing device-dependent image processing techniques is to reduce the power consumption and prolong the battery lifespan, since the display is the most power consuming component in a typical mobile device [8, 9]. To develop a power-efficient RGB-to-RGBW conversion algorithm, we should take different characteristics of display panels into account. For example, a transmissive display, *e.g.*, TFT-LCD, filters light from a light source, which mainly affects the power consumption. On the contrary, an emissive display, *e.g.*, OLED, independently drives each pixel, and the R, G, B subpixels in each pixel have different efficiencies. Since emissive displays, especially OLED, provide superior color reproducibility and power efficiency to transmissive displays in general, emissive displays have been adopted in recent high-end



(a) (b)

Fig. 1. Example subpixel structures of the (a) RGB and (b) RGBW displays.

multimedia devices, including mobile phones and televisions. Moreover, due to these advantages, emissive displays are expected to be used in a wider range of devices in the near future. Therefore, we focus on emissive displays in this work.

While recent researches on RGB-to-RGBW conversion have been focused on minimizing the color distortion and efficient implementation, little work has been done to optimize the color distortion and the power consumption simultaneously. In this work, we propose a power-constrained RGB-to-RGBW conversion scheme for emissive displays. Specifically, we employ a color distortion model in a perceptually uniform color space to quantify the color difference due to the conversion, and then compute the power consumption when the converted RGBW color is displayed. The main contribution of this work is to formulate the optimization problem by incorporating both the perceived color distortion and the power consumption, and to solve it efficiently for real time applications. Simulation results demonstrate that the proposed algorithm can control the power consumption adaptively, and can provide less color distortion than the conventional algorithms even when it reduces the power consumption significantly.

The rest of this paper is organized as follows. Section 2 briefly reviews related work. Section 3 describes the proposed RGB-to-RGBW conversion algorithm. Section 4 provides experimental results. Finally, Section 5 concludes the paper.

2. RELATED WORK

2.1. RGB-to-RGB Conversion

RGB-to-RGBW conversion algorithms take an RGB color value as input and map it to the RGBW value. As Wang *et al.* studied in [4], most conventional RGB-to-RGBW conversion algorithms [2, 5, 6] consist of three steps. First, the white pixel value is extracted as a function of the minimum and maximum intensities among input R, G, and B values. Let us denote $M = \max(R_i, G_i, B_i)$ and $m = \min(R_i, G_i, B_i)$, where R_i, G_i, and B_i are the normalized input light intensities of RGB colors. Then, these conventional algorithms can be written as below according to how they obtain the output light

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intensity of the white color W_o:

$$W_o = m, \tag{1}$$

$$W_o = m^2, \tag{2}$$

$$W_o = -m^3 + m^2 + m, \tag{3}$$

$$W_o = \begin{cases} \frac{mM}{M-m}, & \text{if } \frac{m}{M} < 0.5, \\ M, & \text{otherwise.} \end{cases} \tag{4}$$

Second, the pixel gains are obtained by $K = \frac{W_o+M}{m}$, so that the intensities of the display are increased. Finally, the pixel gains are applied to the input values, and then the output RGBW values are generated by subtracting the white value, which is given by

$$\begin{bmatrix} R_o \\ G_o \\ B_o \end{bmatrix} = K \times \begin{bmatrix} R_i \\ G_i \\ B_i \end{bmatrix} - \begin{bmatrix} W_o \\ W_o \\ W_o \end{bmatrix}, \tag{5}$$

where R_o, G_o, and B_o denote the output light intensities of the RGBW color. Recently, Kwon and Kim [3] proposed a scene-adaptive RGB-to-RGBW conversion method by following a similar procedure. Their algorithm tries to preserve the perceived color within a pre-determined color distortion level based on the retinex theory and maximize the brightness. The existing conversion methods [2–6] aim to increase the brightness while preserving the hue and saturation. Their merits are in implementation simplicity, but they do not *explicitly* minimize perceptual color distortion. Finally, power consumed by the displayed image has not been considered by any of the existing conversion techniques.

2.2. Relation to Prior Work

Motivated by the introduction of the color perception in the human visual system (HVS) in the RGB-to-RGBW conversion [3], we focus on the minimization of the perceptual color distortion during the conversion. In addition to more rigorous distortion modeling in the perceptually linear color space, we try to minimize the power consumption as well when the converted RGBW pixel is represented in an emissive RGBW display. Power-constrained image enhancement has been formulated as convex optimization problems in [10, 11]. We extend the formulation by incorporating both the color distortion and the power consumption into the optimization, while only the luminance component is considered in [10, 11].

3. PROPOSED ALGORITHM

3.1. Color Distortion Model

It is well known that RGB and RGBW displays have different gamuts [3, 12]. Therefore, an RGB value and its corresponding RGBW value may show perceptually different colors. We develop the color distortion model to quantify the perceptual color difference caused by an RGB-to-RGBW conversion. In this work, we assume that the W subpixel emits the same color as the display white point, *e.g.*, D_{65}, and that we use an sRGB display.

We convert both RGB and RGBW colors into a perceptually linear space, so that the perceptual color difference between the input RGB and converted RGBW colors can be measured. To this end, we employ the linearized CIELAB space [13], which approximates the CIELAB uniform color space. Specifically, let $\mathbf{P}_{\text{RGB}} \in \mathbb{R}^{3\times 3}$ and $\mathbf{P}_{\text{RGBW}} \in \mathbb{R}^{3\times 4}$ denote the matrices to convert RGB and RGBW colors, respectively, into the CIEXYZ space. Then, the conversion of the RGB color $\mathbf{x}$ and the RGBW color $\mathbf{y}$ can be written by

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \underbrace{\begin{bmatrix} p_{11} & p_{21} & p_{31} \\ p_{21} & p_{22} & p_{32} \\ p_{31} & p_{23} & p_{33} \end{bmatrix}}_{\mathbf{P}_{\text{RGB}}} \begin{bmatrix} R_i \\ G_i \\ B_i \end{bmatrix}, \tag{6}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \beta \underbrace{\begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \end{bmatrix}}_{\mathbf{P}_{\text{RGBW}}} \begin{bmatrix} R_o \\ G_o \\ B_o \\ W_o \end{bmatrix}, \tag{7}$$

where p_{ij}'s for $1 \leq i, j \leq 3$ are defined in [14], and β is a scaling parameter that considers the ratio of subpixel sizes. Also, in (7), $p_{i4} = \frac{1}{3}\sum_{j=1}^{3} p_{ij}$, assuming that both RGB and RGBW displays use the same sRGB color space. We then convert two colors in (6) and (7) in the CIEXYZ space into the linearized CIELAB color space ($Y_y C_x C_z$) about the D_{65} white point [13], which is given by

$$Y_y = 116\frac{Y}{Y_n} - 16, \tag{8}$$

$$C_x = 500\left[\frac{X}{X_n} - \frac{Y}{Y_n}\right], \tag{9}$$

$$C_z = 200\left[\frac{Y}{Y_n} - \frac{Z}{Z_n}\right], \tag{10}$$

where (X_n, Y_n, Z_n) is the D_{65} white point for the CIEXYZ color space. Since only the perceptual color difference rather than absolute values is considered in this work, we can omit the subtraction in (8) and denote the transformation in (8)∼(10) as linear equations, which is denoted by the matrix $\mathbf{T}_{\text{Lab}} \in \mathbb{R}^{3\times 3}$. Then, we rewrite the conversion from RGB and RGBW colors, respectively, into the linearized CIELAB space compactly in vector notations as

$$\mathbf{T}_{\text{Lab}}\mathbf{P}_{\text{RGB}}\mathbf{x} = \mathbf{b}_{\mathbf{x}}, \tag{11}$$

$$\mathbf{T}_{\text{Lab}}\mathbf{P}_{\text{RGBW}}\mathbf{y} = \mathbf{T}\mathbf{y}, \tag{12}$$

where $\mathbf{T}$ denotes the color space transformation matrix from the RGBW space to the linearized CIELAB space about D_{65} white point, and $\mathbf{b}_{\mathbf{x}}$ is the color vector in the linearized CIELAB space for the input RGB value $\mathbf{x}$.

Finally, the perceptual color distortion $D_{\mathbf{x}}(\mathbf{y})$ due to the RGB-to-RGBW conversion is defined as the Euclidean distance between the input RGB color $\mathbf{x}$ and the converted RGBW color $\mathbf{y}$ in the linearized CIELAB space, given by

$$D_{\mathbf{x}}(\mathbf{y}) = \|\mathbf{T}\mathbf{y} - \mathbf{b}_{\mathbf{x}}\|^2. \tag{13}$$

Remark: Note that, although the linearized transformation in (8)∼(10) expresses the CIELAB color space approximately, it greatly facilitates the formulation of the color distortion as a quadratic form in (13) and subsequently enables a tractable solution via quadratic programming (see Section 3.3).

3.2. Power Consumption Model of Emissive Displays

We model the power consumption in an emissive RGBW display panel, which is required to represent an RGBW pixel. In [15], Dong and Zhong derived a power model for an OLED display. According to their experimental results, power P_{RGB} to display a single pixel can be modeled by

$$P_{\text{RGB}} = \omega_0 + \omega_r R + \omega_g G + \omega_b B, \tag{14}$$

where R, G, and B are the linear red, green, and blue values of the pixel. Also, ω_r, ω_g, ω_b are weighting coefficients that express the different characteristics of red, green, and blue subpixels, and a constant ω_0 accounts for static power consumption, which is independent of pixel values. Note that the power model in (14) can be applicable to not only the OLED but also other emissive displays including PDP and FED [10].

Without loss of generality, we can extend the power model in (14) to emissive RGBW displays, which is given by

$$P_{\mathrm{RGBW}} = \omega_0 + \omega_r R + \omega_g G + \omega_b B + \omega_w W, \tag{15}$$

where W and ω_w are the linear white value of the pixel and the corresponding coefficient, respectively. In this work, since we modify pixel values to find the optimal conversion, we ignore parameter ω_0 for static power consumption. Also, the weighting ratios are set to $\omega_r : \omega_g : \omega_b : \omega_w = 1.58 : 1.07 : 5.32 : 1.00$, which were measured for a particular emissive RGBW display in [16]. Then, the power consumption for displaying the RGBW color $\mathbf{y}$ can be written in a vector notation as

$$P_{\mathrm{RGBW}}(\mathbf{y}) = \boldsymbol{\omega}^T \mathbf{y}, \tag{16}$$

where $\boldsymbol{\omega} = [\omega_r, \omega_g, \omega_b, \omega_w]^T$.

3.3. Constrained Optimization

Let us formulate the power-constrained RGB-to-RGBW conversion for emissive displays as a constrained optimization problem. We have two competing goals: one is to achieve the optimal conversion by minimizing the color distortion $D_{\mathbf{x}}(\mathbf{y})$ in (13), and the other is to reduce the power consumption $P_{\mathrm{RGBW}}(\mathbf{y})$ in (16) for displaying color $\mathbf{y}$. In other words, given the input pixel value $\mathbf{x}$, we should minimize the color distortion $D_{\mathbf{x}}(\mathbf{y})$ subject to the constraint on the power consumption $P_{\mathrm{RGBW}}(\mathbf{y})$. We can solve this constrained optimization problem by minimizing the Lagrangian cost

$$J_{\mathbf{x}}(\mathbf{y}) = \|\mathbf{T}\mathbf{y} - \mathbf{b}_{\mathbf{x}}\|^2 + \lambda \boldsymbol{\omega}^T \mathbf{y}, \tag{17}$$

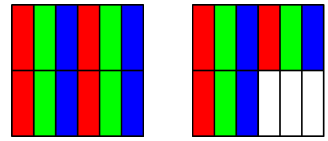
where λ is a Lagrangian multiplier to control the tradeoff between the color distortion and the power consumption. When $\lambda = 0$, the perceived color is perfectly maintained by the conversion without the power constraint. As λ increases, the power term becomes more dominant to reduce the power consumption accordingly.

In addition to minimizing $J_{\mathbf{x}}(\mathbf{y})$ in (17), the RGBW pixel value $\mathbf{y}$ should satisfy a further constraint. That is, the minimum and maximum intensities in $\mathbf{y}$ should be bounded by the minimum and maximum values of displayable range, *i.e.*, 0 and 1, respectively. Therefore, we reformulate the optimization problem as

$$\begin{aligned} \underset{\mathbf{y}}{\text{minimize}} \quad & \|\mathbf{T}\mathbf{y} - \mathbf{b}_{\mathbf{x}}\|^2 + \lambda \boldsymbol{\omega}^T \mathbf{y} \\ \text{subject to} \quad & \mathbf{0} \preceq \mathbf{y} \preceq \mathbf{1}, \end{aligned} \tag{18}$$

where $\mathbf{0}$ and $\mathbf{1}$ are the column vectors, all elements of which are 0 and 1, respectively, and $\preceq$ denotes the element-wise inequality between two vectors.

The optimization problem in (18) is a well-known quadratic programming with inequality constraints, and solvers are readily available that apply numerical algorithms such as the interior-point method [17]. While quadratic programs have known fast solvers, solving the problem in (18) for each pixel in an image is somewhat unrealistic for real-time conversion and display. Instead, we build a color lookup table (LUT), which maps an input RGB color to the output RGBW color. More specifically, we solve the optimization problem in (18) for all possible color inputs $\mathbf{x}$'s and store them with the corresponding outputs $\mathbf{y}$'s. Then, the input RGB image can be converted to the RGBW image with the color LUT in real time. In practice, sparse LUTs with real-time interpolation can be used to facilitate a desirable memory vs. computation trade-off.



(a) (b)

Fig. 2. The arrangement of virtual pixel configurations for the (a) RGB and (b) RGBW displays.

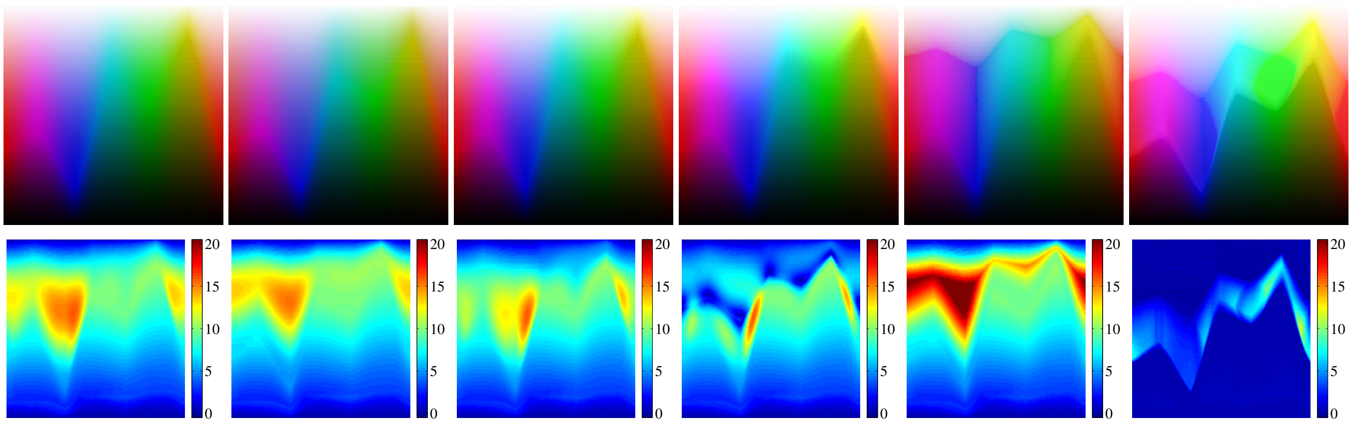
Table 1. Comparison of the Wang *et al.*'s algorithms [4] in (1)$\sim$(4), the Kwon and Kim's algorithm [3], and the proposed algorithm in terms of the average color distortion ΔE_{94}, the 95th percentile ΔE_{94}, and the average power consumption P_{RGBW} on the test images. The results of the proposed algorithm are obtained with two different sizes of LUT, *i.e.*, 256^3 and 32^3, respectively.

		Avg. ΔE_{94}	95% ΔE_{94}	Avg. P_{RGBW}
Conventional	Wang *et al.* in (1)	4.32	7.46	1.34
	Wang *et al.* in (2)	5.40	7.95	1.36
	Wang *et al.* in (3)	3.83	6.71	1.37
	Wang *et al.* in (4)	3.18	5.65	1.37
	Kwon and Kim	5.30	8.54	1.28
Proposed (256^3)	$\lambda = 0$	0.43	0.57	1.61
	$\lambda = 50$	1.56	3.89	1.13
	$\lambda = 100$	3.26	7.49	1.06
Proposed (32^3)	$\lambda = 0$	0.47	0.64	1.61
	$\lambda = 50$	1.50	3.74	1.14
	$\lambda = 100$	3.20	7.38	1.07

4. EXPERIMENTAL RESULTS

We evaluate the performance of the proposed RGB-to-RGBW conversion algorithm by emulating both RGB and RGBW displays as shown in Fig. 2. Specifically, each pixel in the emulated displays are composed of virtual RGB and RGBW pixels, respectively, which are formed by four (2$\times$2) real RGB pixels. While the resolution of an input image is doubled using the nearest-neighbor interpolation for the virtual RGB display, R, G, and B subpixels in a pixel out of four have the same value to express W subpixel value for the virtual RGBW display. We increase the viewing distance of the emulated displays to account for the reduced spatial frequencies in the virtual displays. The parameter β in (7) is fixed to 0.75 in all tests, assuming that the pixel sizes of RGB and RGBW displays are the same. Also, the numbers of RGB nodes in the color LUTs are 32^3 and 256^3.

First, we compare the proposed algorithm with the conventional algorithms using two objective metrics: color distortion against the ground-truth (input) CIELAB color in terms of the CIE94 ΔE (ΔE_{94}) metric (average and 95th percentile) [18] and the power consumption P_{RGBW} in (16). Table 1 lists the average performance over 24 test images from the Kodak Lossless True Color Image



(a) Wang *et al.* in (1) (b) Wang *et al.* in (2) (c) Wang *et al.* in (3) (d) Wang *et al.* in (4) (e) Kwon and Kim (f) Proposed

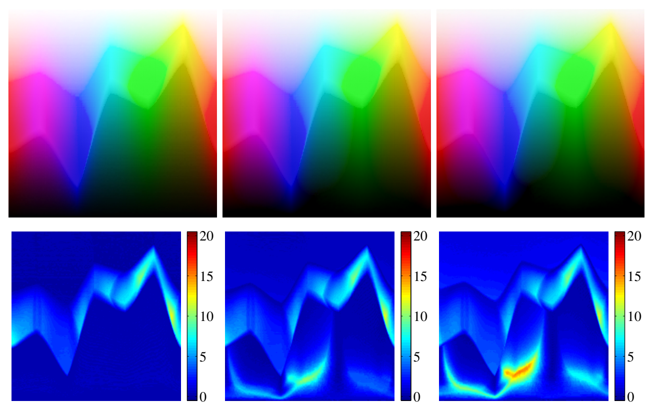
Fig. 3. RGB-to-RGBW conversion results on the sRGB test image. The top row compares the emulation results on the RGBW display, and the bottom row shows the corresponding color distortion ΔE_{94} maps. For the proposed algorithm in (f), $\lambda = 0$ and the number of nodes in the LUT is 256^3.

Suite[1]. ΔE_{94} measures the perceived magnitude of the difference between two colors, and a low value implies that the conversion well preserves the color of an input image. The proposed algorithm significantly outperforms the conventional algorithms in terms of ΔE_{94} at $\lambda = 0$ and 50. In all tests, with the exception for $\lambda = 0$, which does not consider the power consumption, the proposed algorithm consumes the least power. Moreover, we see that the proposed algorithm can achieve more power saving by increasing λ. For example, when $\lambda = 100$, more than 16% of power is saved compared with that of the Kwon and Kim's algorithm [3], which is the most power efficient among the conventional algorithms. In addition, we note that the average power consumption in the RGB display P_{RGB} is 1.91 at the same test condition, which is significantly higher than that of the RGBW display. When the number of nodes in the LUT is reduced to 32^3, the color distortion increases at $\lambda = 0$, but the distortion decreases with the moderate increase in power consumption at $\lambda = 50$ and 100.

Fig. 3 compares the emulation results of the proposed RGB-to-RGBW conversion algorithm with those of the Wang *et al.*'s algorithms in (1)$\sim$(4) and the Kwon and Kim's algorithm [3] on the sRGB test image. The LUT size is 256^3 and the parameter λ in (18) is set to 0 to obtain the results of the proposed algorithm in Fig. 3(f). Fig. 3 also shows the corresponding color distortion ΔE_{94} maps. We see that the proposed algorithm reproduces the input colors more faithfully with less distortion than the conventional algorithms by taking the color distortion into account in the optimization.

Finally, Fig. 4 shows the result images and the corresponding color distortion maps of the proposed algorithm for three different values of λ. When $\lambda = 0$, the proposed algorithm yields the best results to minimize the color distortion. On the contrary, as λ gets higher, the proposed algorithm saves more power with increased color distortion. However, we note that it is hard to notice differences between the case without the power constraint ($\lambda = 0$) and the case when $\lambda = 100$. More specifically, the average ΔE_{94} values for the sRGB test image are 1.24, 1.93, and 2.71, respectively, while the average power consumptions are 3.51, 3.43, and 3.33, respectively.

[1]http://r0k.us/graphics/kodak/



(a) $\lambda = 0$ (b) $\lambda = 50$ (c) $\lambda = 100$

Fig. 4. The result images of the proposed algorithm for $\lambda = 0$, 50, and 100. The top row corresponds to the emulation results, and the bottom row shows the corresponding color distortion ΔE_{94} maps.

5. CONCLUSIONS

We develop a new constrained optimization based technique to enable power-constrained RGB-to-RGBW conversion algorithm for emissive displays. We employ a visually meaningful color distortion model to capture the perceptual color difference due to the conversion. The power consumption of emissive RGBW displays gets modeled as a linear constraint on the vector of RGBW values. Finding the best RGBW value to display corresponding to an input RGB value then reduces to a convex quadratic program and hence is tractably solved. Practical image conversion can be achieved by pre-solving the problem for a set of RGB values and storing them on a color LUT. Our proposed optimization can be used to create LUTs that enable significantly more accurate color conversion than existing alternatives. Further, the framework enables a graceful trade-off between minimizing color distortion in the conversion and the associated power consumption of a displayed RGBW image.

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