Time-Stable RGB LED Backlighting Control Using Time-Varying Transform Matrix

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Abstract

This paper proposes a driving current control method for a back light unit (BLU), consisting of red, green, and blue (RGB) light-emitting diodes (LEDs), whereby an RGB optical sensor is used to check the output color stimulus variation to enable a time-stable color stimulus for light emission by the RGB LED BLU. First, to obtain the present color stimulus information of the RGB LED BLU, an RGB to XYZ transform matrix is derived to enable CIEXYZ values to be calculated for the RGB LED BLU from the output values of an RGB optical sensor. The elements of the RGB to XYZ transform matrix are polynomial coefficients resulting from a polynomial regression. Next, to obtain the proper duty control values for the current supplied to the RGB LEDs, an XYZ to Duty transform matrix is derived to calculate the duty control values for the RGB LEDs from the target CIEXYZ values. The data used to derive the XYZ to Duty transform matrix are the CIEXYZ values for the RGB LED BLU estimated from the output values of the RGB optical sensor and corresponding duty control values applied to the RGB LEDs for the present, first preceding, and second preceding sequential check points. With every fixed-interval check of the color stimulus of the RGB LED BLU, the XYZ to Duty transform matrix changes adaptively according to the present lighting condition of the RGB LED BLU, thereby allowing the RGB LED BLU to emit the target color stimulus in a time-stable format, regardless of changes in the lighting condition of the RGB LEDs.

Introduction

The interest for using light-emitting diodes (LEDs) for display and illumination applications has been growing steadily over the past few years. The potential for long life-time, reduced energy consumption, robustness, and with no Hg are positive attributes of this rapidly evolving technology that have generated so much interest for its use in a variety of applications [1]. The use of LEDs for the backlighting in liquid crystal display (LCD) applications offers more interesting advantages.

The performance of color reproduction for the red, green, and blue (RGB) LED backlight is better than that of cold-cathode fluorescent lamps (CCFLs) backlight. The color reproduction capability is expressed as a color gamut which is generally depicted by a triangle of primary colors in displays. The value of a color gamut is simply expressed as a percentage between the area of triangle of a display and the area of triangle of a reference color space, such as the National Television Systems Committee (NTSC) standard. The color gamut of the RGB LED backlight can cover nearly 100% of the NTSC [2].

Essentially, since LCDs are hold-type displays while cathode ray tubes (CRTs) are impulse-type displays, motion blur is a more serious problem in LCDs than it is in CRTs. To reduce motion blur in LCDs, the LED backlighting can be helpful used for high frequency driving, in the technique of backlight blinking [3]. Backlight modulation not only works for improving motion blur, but also contributes to a higher contrast ratio and lower power consumption. A whole screen is divided into some areas and LEDs are assembled on each one with independent brightness control operation. By actively controlling the area-brightness of the LEDs corresponding to the display input signals, the contrast ratio of LCDs can be improved [4].

Although LEDs offer various advantages for backlighting, the use of LEDs as a backlighting source has several limitations, one of which is lighting stability. Due to inherent characteristics, the lighting produced by LEDs depends on the temperature and lighting time. The intensity of the output light of LEDs increases with low temperature while it decreases with high temperature. Therefore, under the condition that the temperature of LEDs can not be a constant, it is difficult to make the intensity of the LED backlighting stable. Also, according to the temperature of LEDs, the wavelength of the peak in the spectral power distribution of the LED light shift. Because the directions and amounts of shifted wavelength of the red, green, and blue LED are different from each other, the chromaticity of the RGB LED BLU can be changed by the temperature variation. Moreover, LEDs depend on their lighting time. As the lighting time for LEDs increases, the intensity of the output light of LEDs decreases [5], [6].

Accordingly, for a time-stable RGB LED BLU output, this paper proposes a driving current control method by generating proper duty control values under the present lighting condition of an RGB LED BLU. To check the present output color stimulus of the RGB LED BLU, the forward characterization of the RGB optical sensor is performed. According to the checked present lighting condition of the RGB LED BLU, the proper duty control values are generated using a real-time-update *XYZ to Duty* transform matrix. Experimental results demonstrate that the proposed duty control method enables a time-stable RGB LED BLU emission.

Time-Stability for RGB LED BLU

To observe the variation of the output color stimulus for the RGB LED back light unit (BLU) with time, the duty control values for the RGB LEDs are fixed to (2800, 2000, 3200) where the maximum duty control value is 4095 in 12-bit format. Then, the RGB LED BLU was turned on and the output CIEXYZ color stimulus values and the spectral power distribution for the RGB LED BLU lighting were measured with a constant time interval of 10 minutes using a Minolta CS-1000 spectroradiometer. As shown in Table 1, the measured CIEXYZ values for the RGB LED BLU are changing continuously with time. After roughly 90 minutes, the CIEXYZ values become stable. This means the temperature of the RGB LED BLU does not change after 90 minutes, consequently, the variation of the color stimulus of the RGB LED BLU caused by changes of temperature does not occur after that time. If the temperature condition of the RGB LED BLU is changed by an internal or external factor, the constant output color stimulus of the RGB LED BLU cannot be guaranteed however. Figure 1 shows the different spectral power distributions of RGB LED BLU with time.

Table 1. Change of CIEXYZ values of RGB LED BLU with time

Time [minutes]	X	Y	Z
0	6464	6469	11710
10	6308	6334	11610
20	6202	6242	11550
30	6125	6175	11510
:	:	:	:
90	5818	5901	11410
100	5818	5901	11410
110	5818	5901	11410
120	5817	5900	11410

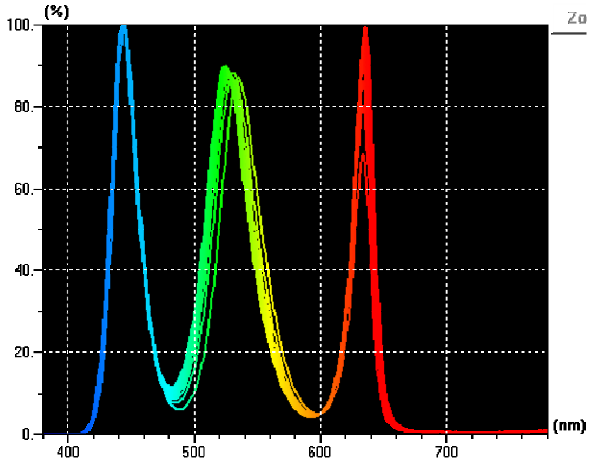

Figure 1. *Change of spectral power distribution of RGB LED BLU with time*

Proposed Control Method for Time-Stable RGB LED Backlighting

Figure 2 shows a flow chart of the proposed method for the duty control of the driving current for time-stable lighting of an RGB LED BLU. First, the present output values of an RGB optical sensor are obtained to check the present lighting condition of the RGB LED BLU. Based on the output values obtained from the RGB optical sensor, the present CIEXYZ values for the RGB LED BLU are estimated by performing a linear operation in a matrix form using an *RGB to XYZ* transform matrix. Next, an *XYZ to Duty* transform matrix is updated adaptively according to the present lighting condition of the RGB LED BLU using the CIEXYZ values for the RGB LED BLU and corresponding duty control values applied to the RGB LEDs for the present, first preceding, and second preceding check points. From the target CIEXYZ values, the proper duty control values are then calculated by performing a linear operation in a matrix form using an *XYZ to Duty* transform matrix. After these duty control values are applied to the RGB LEDs, the overall procedure is iterated continuously.

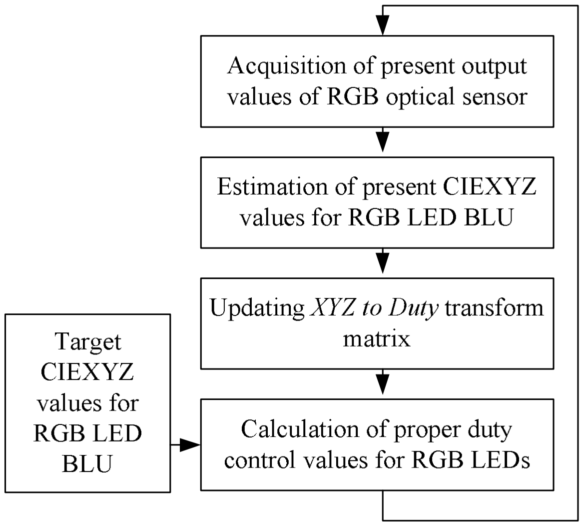

Figure 2. *Flow chart of the proposed method*

Forward Characterization of RGB Optical Sensor

To check the present lighting condition of the RGB LED BLU, the forward characterization of the RGB optical sensor to estimate the present CIEXYZ values for the RGB LED BLU using the output values of the RGB optical sensor should be performed. From the arbitrary output values of the RGB optical sensor, to estimate the CIEXYZ values for the RGB LED BLU, first, 64 sample patches on the RGB LED BLU are generated by various combinations of the duty control values of the RGB LEDs. For those sample patches, the output values of the RGB optical sensor are obtained and the CIEXYZ values are measured simultaneously to each other by a spectroradiometer. Figure 3 shows the measurement environment for the RGB optical sensor characterization. The measurement is performed in a dark room. The RGB optical sensor is located on the lower side of the RGB LED BLU to avoid obstructing the RGB LED BLU lighting by the RGB optical sensor while the measurement point of the spectroradiometer is the center of the RGB LED BLU. The distance between the sample patch of the RGB LED BLU and the spectroradiometer is four times the RGB LED BLU height.

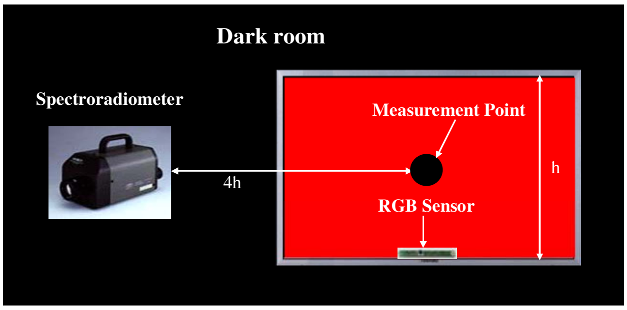

Figure 3. *Measurement environment for RGB optical sensor characterization*

Using the 64 couples of the measured CIEXYZ values and the output values of the RGB optical sensor for each sample patch, the *RGB to XYZ* transform matrix between the RGB sensor output values and the corresponding CIEXYZ values can be generated. The *RGB to XYZ* transform matrix is obtained as follows:

$$\begin{bmatrix} RGB\,to\,XYZ \end{bmatrix} = \begin{bmatrix} X_1 & X_2 & \cdots & X_n \\ Y_1 & Y_2 & \cdots & Y_n \\ Z_1 & Z_2 & \cdots & Z_n \end{bmatrix} \begin{bmatrix} 1 & R_1 & G_1 & B_1 \\ 1 & R_2 & G_2 & B_2 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & R_n & G_n & B_n \end{bmatrix} \cdot \left(\begin{bmatrix} 1 & 1 & \cdots & 1 \\ R_1 & R_2 & \cdots & R_n \\ G_1 & G_2 & \cdots & G_n \\ B_1 & B_2 & \cdots & B_n \end{bmatrix} \begin{bmatrix} 1 & R_1 & G_1 & B_1 \\ 1 & R_2 & G_2 & B_2 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & R_n & G_n & B_n \end{bmatrix} \right)^{-1} \quad (1)$$

where n is the number of sample patches on the RGB LED BLU generated by various combinations of the duty control values of the RGB LEDs. Here, 64 (4×4×4) sample patches were used, and $[R_k\ G_k\ B_k]$ and $[X_k\ Y_k\ Z_k]$ mean the output values of the RGB optical sensor and measured CIEXYZ values for the k^{th} sample patch, respectively. Consequently, the size of the *RGB to XYZ* transform matrix becomes 3×4. Generally, the larger size of the transform matrix, the smaller the estimation error. However, as shown in Table 2, a 3×4 transform matrix is suitable for this application, due to the linear relationship between the output values of the RGB optical sensor and the measured CIEXYZ values for the sample patches on the RGB LED BLU. Both the average and maximum CIELAB color differences between measured and estimated CIEXYZ values for 64 sample patches are below 1 when using the 3×4 transform matrix. The color differences for the 3×6 transform matrix are larger than those for the 3×4 transform matrix.

Table 2. Color differences between measured and estimated CIEXYZ values according to matrix size used

Matrix size	Average ΔE_{ab}	Maximum ΔE_{ab}
3×3	0.9178	4.3103
3×4	0.2879	0.9118
3×6	0.3425	2.0279
3×8	0.2443	1.0464
3×9	0.2527	1.5835
3×11	0.1693	0.6254
3×14	0.1136	0.4191
3×20	0.1124	0.4081

As shown in Table 3, because the transform polynomials of larger than 3×4 sized *RGB to XYZ* transform matrices are composed of quadratic or/and cubic terms as well as linear terms, using larger than 3×4 sized *RGB to XYZ* transform matrices is not effective to model the linear relationship between the output values of the RGB optical sensor and the measured CIEXYZ values.

The 3×4 *RGB to XYZ* transform matrix is used to estimate the CIEXYZ values from the output values of the RGB optical sensor as follows:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} RGB\,to\,XYZ \end{bmatrix} \begin{bmatrix} 1 \\ R \\ G \\ B \end{bmatrix} \quad (2)$$

Table 3. Transform polynomials according to matrix size used

Size of transform matrix	Transform polynomial
3×3	$P(R, G, B) = c_1R+c_2G+c_3B$
3×4	$P(R, G, B) = c_0+c_1R+c_2G+c_3B$
3×6	$P(R, G, B) = c_1R+c_2G+c_3B+c_4RG+c_5GB+c_6BR$
3×8	$P(R, G, B) = c_0+c_1R+c_2G+c_3B+c_4RG+c_5GB +c_6BR+c_{10}RGB$
3×9	$P(R, G, B) = c_1R+c_2G+c_3B+c_4RG+c_5GB+c_6BR +c_7R^2+c_8G^2+c_9B^2$
3×11	$P(R, G, B) = c_0+c_1R+c_2G+c_3B+c_4RG+c_5GB +c_6BR+c_7R^2+c_8G^2+c_9B^2+c_{10}RGB$
3×14	$P(R, G, B) = c_0+c_1R+c_2G+c_3B+c_4RG+c_5GB +c_6BR+c_7R^2+c_8G^2+c_9B^2+c_{10}RGB +c_{11}R^3+c_{12}G^3+c_{13}B^3$
3×20	$P(R, G, B) = c_0+c_1R+c_2G+c_3B+c_4RG+c_5GB +c_6BR+c_7R^2+c_8G^2+c_9B^2+c_{10}RGB +c_{11}R^3+c_{12}G^3+c_{13}B^3+c_{14}RG^2+c_{15}R^2G +c_{16}GB^2+c_{17}G^2B+c_{18}BR^2+c_{19}B^2R$

Inverse characterization of RGB LED BLU

To enable a time-stable color stimulus for light emission of the RGB LED BLU by controlling the driving current of RGB LEDs, only the duty control values for the current supplied to the RGB LEDs are varied while the intensities of the current for the RGB LEDs are fixed to constant values. To obtain the proper duty control values of the RGB LEDs that makes the RGB LED BLU have the target CIEXYZ values, a 3×3 matrix to transform the target CIEXYZ values into the corresponding duty control values of the RGB LEDs is used. The size of the *XYZ to Duty* transform matrix is 3×3, which is suitable for this application, due to the linear relationship between the input duty control values and the corresponding output CIEXYZ values. Generally, the *XYZ to Duty* transform matrix is obtained as follows:

$$\begin{bmatrix} XYZ\,to\,Duty \end{bmatrix} = \begin{bmatrix} X_{R,\max} & X_{G,\max} & X_{B,\max} \\ Y_{R,\max} & Y_{G,\max} & Y_{B,\max} \\ Z_{R,\max} & Z_{G,\max} & Z_{B,\max} \end{bmatrix}^{-1} \quad (3)$$

Table 4. Results of duty control

D_R	D_G	D_B	X	Y	Z	ΔE_{ab}	Δxy	$\Delta u'v'$
3153	1822	3206	6601.11	5991.83	11869.70	0.082	0.00016	0.00011
3165	1825	3210	6608.45	5995.51	11874.10	0.038	0.00007	0.00005
3170	1827	3212	6607.02	5994.12	11872.77	0.045	0.00008	0.00007
3202	1839	3225	6619.20	6002.60	11888.76	0.110	0.00012	0.00012
3214	1845	3228	6601.42	5993.76	11869.13	0.105	0.00015	0.00012
3218	1846	3230	6603.41	5995.49	11869.02	0.096	0.00011	0.00010
3229	1849	3233	6600.54	5990.21	11863.89	0.066	0.00009	0.00006
3235	1852	3236	6597.81	5988.96	11865.48	0.099	0.00018	0.00013
3244	1855	3239	6597.21	5987.12	11862.80	0.089	0.00016	0.00011
3256	1860	3245	6607.96	5995.79	11880.15	0.054	0.00015	0.00010

where [$X_{P,\max}$ $Y_{P,\max}$ $Z_{P,\max}$], $P=R$, G, and B, are the CIEXYZ values of the RGB LED BLU for the maximum duty control values of the red, green, and blue LEDs, respectively. However, if constant duty control values are applied to the RGB LEDs, the CIEXYZ values of the RGB LED BLU become time-varied rather than constant because of changes in the lighting condition of the RGB LEDs. Therefore, to obtain duty control values for constant target CIEXYZ values, a time-varying *XYZ to Duty* transform matrix according to the present lighting condition of the RGB LED BLU is required, instead of a constant *XYZ to Duty* transform matrix. Namely, the present lighting condition of the RGB LED BLU is periodically checked, and the *XYZ to Duty* transform matrix adaptively updated accordingly. This *XYZ to Duty* transform matrix is proposed as follows:

$$\begin{bmatrix} & & \\ XYZ\,to\,Duty & & \\ & & \end{bmatrix} = \begin{bmatrix} D_R[n] & D_R[n-1] & D_R[n-2] \\ D_G[n] & D_G[n-1] & D_G[n-2] \\ D_B[n] & D_B[n-1] & D_B[n-2] \end{bmatrix} \cdot \begin{bmatrix} X_O[n] & X_O[n-1] & X_O[n-2] \\ Y_O[n] & Y_O[n-1] & Y_O[n-2] \\ Z_O[n] & Z_O[n-1] & Z_O[n-2] \end{bmatrix}^{-1} \quad (4)$$

where [n] represents the present check point, [n-1] and [n-2] mean the first and second preceding check points, respectively, D_R, D_G, and D_B represent the input duty control values for the red, green, and blue LEDs, and X_O, Y_O, and Z_O represent the corresponding output CIEXYZ values for the RGB LED BLU. As such, $D_R[n]$, $D_G[n]$, and $D_B[n]$ are the present duty control values, while $X_O[n]$, $Y_O[n]$, and $Z_O[n]$ are the present CIEXYZ values for the RGB LED BLU. For every check point, the *XYZ to Duty* transform matrix is updated using the duty control values and CIEXYZ values for the three latest check points, and the oldest duty control values and CIEXYZ values are discarded when new duty control values and CIEXYZ values are used in equation 4. Thus, on the right side of equation 4, the latest duty control values and CIEXYZ values are inserted into the first column, thereby shifting the previously entered elements one column to the right and automatically eliminating the oldest elements from each matrix.

The *RGB to XYZ* transform matrix is then used to generate duty control values for the RGB LED BLU to keep the target CIEXYZ values as follows:

$$\begin{bmatrix} D_R \\ D_G \\ D_B \end{bmatrix} = \begin{bmatrix} & & \\ & XYZ\,to\,Duty & \\ & & \end{bmatrix} \begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} \quad (5)$$

where X_T, Y_T, and Z_T are the target CIEXYZ values for the RGB LED BLU.

Experimental Results

In experiments, the target CIEXYZ values were set at (6612, 6000, 11878), the luminance at 6000cd/m^2, and the *xy* chromaticity coordinates at (0.270, 0.245). Table 4 shows the generated duty control values, output CIEXYZ values for the RGB LED BLU, color differences in CIELAB color space, and *xy* and *u'v'* chromaticity plane between the output color values and the target color values for 10 check points. The CIEXYZ values of the reference white used to obtain the color differences in CIELAB was (9039, 11060, 15020) which is attainable by the maximum duty control values of (4095, 4095, 4095). Overall, the CIELAB color differences were smaller than 0.2 and the Δxy and $\Delta u'v'$ below 0.0002.

Conclusions

This paper proposed a driving current control method for a constant RGB LED BLU output by generating proper duty control values under the present lighting condition of an RGB LED BLU. An *RGB to XYZ* transform matrix is used to obtain the present CIEXYZ values for the RGB LED BLU from the output values of an RGB optical sensor, while a real-time-update *XYZ to Duty* transform matrix is used to generate proper duty control values according to the present lighting condition of the RGB LED BLU. Experiments confirmed that the proposed duty control method enabled a stable RGB LED BLU emission. The average color differences in CIELAB space and the chromaticity plane between the output color values and the target color values were about 0.1 and 0.0001, respectively. In general, a CIELAB color difference under 1 is imperceptible to the human eye [7].

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