Journal of Imaging Science and Technology® 53(3): 030503–030503-5, 2009.

Time-Stable Red, Green, and Blue Light-Emitting Diode 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 a 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 a 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. © 2009 Society for Imaging Science and Technology.*
[DOI: 10.2352/J.ImagingSci.Technol.2009.53.3.030503]

INTRODUCTION

Interest in light-emitting diodes (LEDs) for display and illumination applications has continued to grow over the past few years, due to their potential as regards a long life-time, reduced energy consumption, robustness, and lack of mercury.[1] Meanwhile, the use of LEDs for backlighting in liquid crystal display (LCD) applications offers even more interesting advantages, as the color reproduction performance of red, green, and blue (RGB) LED backlights is better than that of cold-cathode fluorescent lamp backlights. The color reproduction capability of a display is expressed as a color gamut, which is generally depicted by a triangle of primary colors, where the value of a color gamut is simply expressed as the percentage between the area of the triangle of the display and the area of the triangle of a reference color space, such as the National Television Systems Committee (NTSC) standard. The color gamut of RGB LED backlighting can cover nearly 100% of the NTSC.[2]

Furthermore, since LCDs are essentially hold-type displays, while cathode ray tubes (CRTs) are impulse-type displays, motion blur is a more serious problem for LCDs than for CRTs. Thus, to reduce the motion blur in LCDs, LED backlighting can be helpful for high frequency driving using the technique of backlight blinking.[3] Plus, backlight modulation not only improves motion blur, but also contributes to a higher contrast ratio and lower power consumption. The whole screen is divided into different areas, and the LEDs assembled in each area are operated under independent brightness control. As a result, the active control of the area-brightness of the LEDs corresponding to the display input signals improves the contrast ratio of the LCD.[4]

Nonetheless, 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 a low temperature, yet decreases with a high temperature. Therefore, in the case of a fluctuating LED temperature, stabilizing the intensity of the LED backlighting becomes difficult. In addition, the peak wavelengths in the spectral power distribution of the LED light shift according to the temperature of the LEDs, and since the direction and amount of the wavelength shifts differ for the red, green, and blue LEDs, the chromaticity of the RGB LED back light unit (BLU) can also change with a temperature variation. Moreover, as the lighting time of a LED increases, the intensity of the output light of the LED decreases.[5,6]

Accordingly, to achieve a time-stable RGB LED BLU output, this paper proposes a driving current control method that generates proper duty control values under the present lighting condition of a RGB LED BLU. To check the present output color stimulus of the RGB LED BLU, inverse characterization is performed using a RGB optical sensor. Based on the checked present lighting condition of the RGB LED BLU, proper duty control values are then generated

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Received Aug. 18, 2008; accepted for publication Feb. 11, 2009; published online Apr. 23, 2009.
1062-3701/2009/53(3)/030503/5/$20.00.

Table I. Change in CIEXYZ values of RGB LED BLU with time.

Time [min]	*X*	*Y*	*Z*
0	6464	6469	11,710
10	6308	6334	11,610
20	6202	6242	11,550
30	6125	6175	11,510
⋮	⋮	⋮	⋮
90	5818	5901	11,410
100	5818	5901	11,410
110	5818	5901	11410
120	5817	5900	11,410

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.

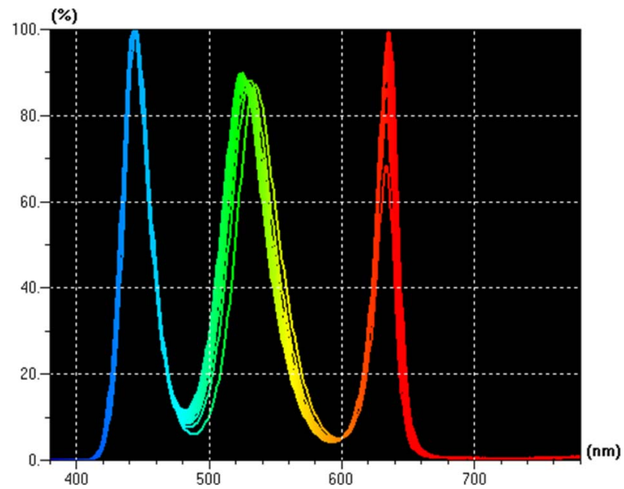

Figure 1. Change in spectral power distribution of RGB LED BLU with time.

TIME STABILITY FOR RGB LED BLU

To observe the variation in the output color stimulus of a RGB LED BLU over time, the duty control values for the RGB LEDs were fixed at (2800, 2000, 3200), where the maximum duty control value was 4095 in a 12-bit format. The RGB LED BLU was then turned on, and the output CIEXYZ color stimulus values and spectral power distribution of the RGB LED BLU lighting measured at intervals of 10 min using a Minolta CS-1000 spectroradiometer. As shown in Table I, the CIEXYZ values measured for the RGB LED BLU were changing continuously with time, then became stable after roughly 90 min. As such, this means that the temperature of the RGB LED BLU did not change after 90 min, thereby eliminating the variation in the color stimulus of the RGB LED BLU. Nonetheless, 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. Figure 1 shows the different spectral power distributions of the 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 a RGB LED BLU. First, the present output values of a 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.

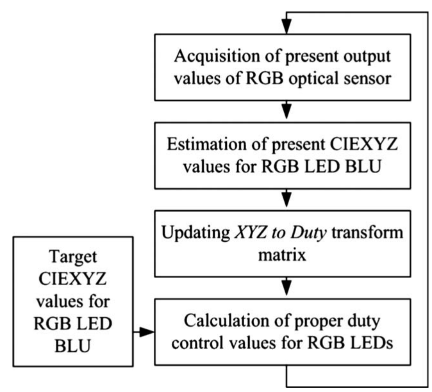

Figure 2. Flow chart of proposed method.

INVERSE CHARACTERIZATION OF RGB OPTICAL SENSOR

To check the present lighting condition of the RGB LED BLU, inverse characterization was performed using a RGB optical sensor to estimate the present CIEXYZ values of the RGB LED BLU. To enable the CIEXYZ values for the RGB LED BLU to be estimated using arbitrary output values from the RGB optical sensor, 64 sample patches were first generated on the RGB LED BLU using various combinations of duty control values for the RGB LEDs. The output values of the RGB optical sensor were then obtained for those patches, along with the CIEXYZ values measured using a spectroradiometer. Figure 3 shows the measurement environment for the RGB optical sensor characterization, which was performed in a dark room. The RGB optical sensor was located on the lower side of the RGB LED BLU to avoid obstructing the RGB LED BLU lighting, while the measure-

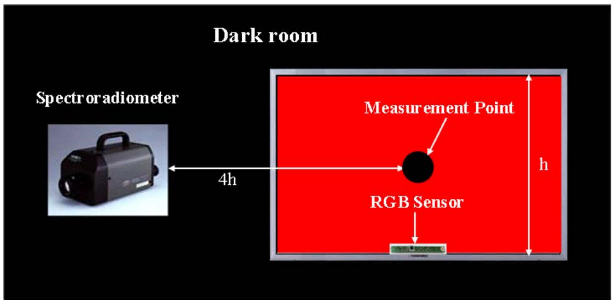

Figure 3. Measurement environment for RGB optical sensor characterization.

ment point for the spectroradiometer was in the center of the RGB LED BLU. The distance between the sample patches on the RGB LED BLU and the spectroradiometer was four times the RGB LED BLU height.

Using the 64 pairs of measured CIEXYZ values and output values from the RGB optical sensor for each sample patch, an *RGB to XYZ* transform matrix between the RGB sensor output values and the corresponding CIEXYZ values was generated. The *RGB to XYZ* transform matrix was obtained as follows:

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

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 ($4\times4\times4$) sample patches were used, and $[R_kG_kB_k]$ and $[X_kY_kZ_k]$ mean the output values of the RGB optical sensor and measured CIEXYZ values for the kth sample patch, respectively. Consequently, the size of the *RGB to XYZ* transform matrix becomes 3×4. Generally, the larger the size of the transform matrix, the smaller the estimation error. However, as shown in Table II, a 3×4 transform matrix was 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. The average and maximum CIELAB color differences between the measured and estimated CIEXYZ values for the 64 sample patches were both below unity when using a 3×4 transform matrix. The color differences for a 3×6 transform matrix were larger than those for a 3×4 transform matrix. As shown in Table III, since the transform polynomials from *RGB to XYZ* transform matrices larger than 3×4 were composed of quadratic or/and cubic terms, as well as linear terms, *RGB to XYZ* transform matrices larger than 3×4 were not effective to model the linear relationship between the output values of the RGB optical sensor and the measured CIEXYZ values. Thus, a 3×4 *RGB to XYZ* transform matrix was used to estimate the CIEXYZ values from the output values of the RGB optical sensor as follows:

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

Matrix sizes	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

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

INVERSE CHARACTERIZATION OF RGB LED BLU

To enable a time-stable color stimulus for light emission by the RGB LED BLU based on controlling the driving current of the RGB LEDs, the duty control values for the current supplied to the RGB LEDs were varied, while the intensities of the current for the RGB LEDs were fixed at constant values. To obtain the proper duty control values for the RGB LEDs to produce the target CIEXYZ values for the RGB LED BLU, a 3×3 *XYZ to Duty* transform matrix was used to transform the target CIEXYZ values into the corresponding duty control values for the RGB LEDs. 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:

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

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

Table III. Transform polynomials according to matrix size used.

Sizes 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	$P(R,G,B)=c_0+c_1R+c_2G+c_3B+c_4RG+c_5GB$ $+c_6BR+c_7R^2+c_8G^2+c_9B^2+c_{10}RGB$ $+c_{11}R^3+c_{12}G^3+c_{13}B^3+c_{14}RG^2+c_{15}R^2G$ $+c_{16}GB^2+c_{17}G^2B+c_{18}BR^2+c_{19}B^2R$

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:

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

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 Eq. (4). Thus, on the right side of Eq. (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 *XYZ to Duty* transform matrix is then used to generate duty control values for the RGB LED BLU to keep the target CIEXYZ values as follows:

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

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, 11,878), the luminance at 6000 cd/m^2, and the xy chromaticity coordinates at (0.270, 0.245). The time interval between the check points was 5 s, which was selected to demonstrate the change in the duty control values, as shown in Table IV. The shorter the time interval, the smaller the change in the duty control values. Table IV 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 ten check points. The CIEXYZ values of the reference white used to obtain the color differences in CIELAB were (9039, 11,060, 15,020), which were attained using 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.

Table IV. 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	11,869.70	0.082	0.00016	0.00011
3165	1825	3210	6608.45	5995.51	11,874.10	0.038	0.00007	0.00005
3170	1827	3212	6607.02	5994.12	11,872.77	0.045	0.00008	0.00007
3202	1839	3225	6619.20	6002.60	11,888.76	0.110	0.00012	0.00012
3214	1845	3228	6601.42	5993.76	11,869.13	0.105	0.00015	0.00012
3218	1846	3230	6603.41	5995.49	11,869.02	0.096	0.00011	0.00010
3229	1849	3233	6600.54	5990.21	11,863.89	0.066	0.00009	0.00006
3235	1852	3236	6597.81	5988.96	11,865.48	0.099	0.00018	0.00013
3244	1855	3239	6597.21	5987.12	11,862.80	0.089	0.00016	0.00011
3256	1860	3245	6607.96	5995.79	11,880.15	0.054	0.00015	0.00010

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 a 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 a 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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