Illumination and Color Control in Red-Green-Blue Light-Emitting Diode

Chun-Wen Tang, Bin-Juine Huang, and Shang-Ping Ying

Abstract—The concept of red-green-blue (RGB) light-emitting-diode (LED) lighting has gained wide attention during recent years and is now one of the targets for future lighting solutions. However, the self-heating of LEDs and environmental temperature variation lead to luminous intensity droop and lighting color drift. The main purpose of this research is to investigate a novel flux feedback and temperature feed-forward (FFB&TFF) control structure for RGB LED lighting control system, in order to provide a wide color range of input commands and regulation of both luminous and color outputs. The work in this paper was carried out in three main steps. First, a thermal–electrical–luminous–chromatic model was derived and identified for RGB LED luminaire. Second, a converter and a compensator were derived and applied to input command conversion and temperature compensation, respectively. Finally, a diagonal proportional–integral controller designed by the decentralized control approach was implemented to regulate the lighting outputs of luminous intensity and chromaticity coordinates in CIE 1976 Uniform Chromaticity Space (UCS) diagram. The results of transient and steady-state experiments showed that the proposed control system was effective.

Index Terms—Decentralized control approach, flux feedback and temperature feed-forward (FFB&TFF), red-green-blue (RGB) light-emitting-diodes (LEDs), system identification, thermal–electrical–luminous–chromatic model.

I. INTRODUCTION

LIGHT-EMITTING diodes (LEDs) are a highly effective lighting technology. Energy saving and long lifetimes are the main advantages in lighting applications. Red-green-blue (RGB) LED lighting is one of the most popular techniques for white light in the application of LCD backlighting, video projection and general lighting. Its chromatic changeability and wide color range can provide unique lighting experiences [1]. However, the luminous and color outputs are easily affected by self-heating of LEDs as well as environmental temperature variations [2], [3]. Thus, a control system for RGB LEDs is called for to regulate both luminous and color outputs. The key issue of effective regulation is a proper control structure design.

Several studies in the literature have proposed and compared to four control structures [4]–[10], that is, flux feedback (FFB), temperature feed-forward (TFF), FFB and temperature feed-forward (FFB&TFF), and color coordinates feedback (CCFB). Both FFB&TFF and CCFB algorithms have shown better color stability. Because of easy implementation, CCFB methods have been studied by several authors [4]–[15] and shown effective color accuracy. However, the accuracy of color output would be restricted by temperature effect [7], inverted sensor matrix [6], [7], and spectra responses mismatch of the filtered color sensor [6], [8]. The FFB&TFF method can avoid those drawbacks but require complex flux measuring technique [7]. Moreover, an algorithm of temperatures to color control commands instead of CCFB must be derived. Wang *et al.* [15] adopted a static lookup table as feed-forward compensator for FFB&TFF method to implement the algorithm and input command conversion. However, the lookup table designed at 25 fixed operating conditions would confine the color range of the input commands. Therefore, the aim of this research is further to investigate a novel FFB&TFF control structure that can apply a wide color range of input commands and achieve transient and steady-state requirements of both luminous and color outputs. The effect is experimentally verified.

The paper is organized as follows. In Section II, a novel FFB&TFF control system with a thermal–electrical–luminous–chromatic model of RGB LED luminaire, a converter, and a compensator is proposed. In Section III, the system identification of the RGB LED luminaire, the converter, and the compensator are presented. In Section IV, the controller design is further introduced. In Section V, the designed control system is implemented for performance analysis. Finally, some conclusions are drawn in Section VI.

II. SYSTEM DESCRIPTION AND MODELING

A. System Description

In this study, a novel FFB&TFF control structure of RGB LED lighting is proposed as shown in Fig. 1, in which T_{CCR} and Φ_r represent the correlated color temperature (CCT) command and total luminous intensity command, respectively, and $T_{CC,OUT}$ and Φ_{OUT} represent CCT output and total luminous intensity output for lighting, respectively. A converter N is applied to transform from T_{CCR} and Φ_r to three dependent signals: converted radiant power L_A , converted electrical power P_A , and converted junction temperature T_A . A compensator M is applied to obtain the radiant compensation L_M to compensate the L_A , by using the junction temperature of RGB LEDs T_{LED} , the electrical power of RGB LEDs P_{LED} , converted electrical

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Fig. 1. Control structure of the RGB LED lighting control system (Solid lines: scalar signals; mesh lines: vector signals).

power P_A , and converted junction temperature T_A . The radiant command $L_C = L_A + L_M$ is a reference which leads $T_{CC,OUT}$ and Φ_{OUT} following $T_{CC,r}$ and Φ_r , respectively. The controller K is adopted to calculate a relevant P_{LED} according to the error signal e . The dynamics of RGB LED luminaire are modeled as G_{LED} with two outputs: Φ_{OUT} as luminous output; and chromaticity coordinate in CIE1976 Uniform Chromaticity Space (UCS) diagram $[u'_{OUT}, v'_{OUT}]^T$ as color outputs. The $T_{CC,OUT}$ is transformed from $[u'_{OUT}, v'_{OUT}]^T$ by using a chromatic transformer F . The FFB loop carries out the radiant power of RGB LEDs L_S , acquired from the luminous intensity of RGB LEDs Φ_{LED} , tracking L_C to regulate Φ_{OUT} ; moreover, the TFF loop performs $T_{CC,OUT}$ following $T_{CC,r}$ since the M provides accurate L_M . Furthermore, a proper controller of FFB loop can guarantee transient and steady-state performance of Φ_{OUT} and $T_{CC,OUT}$.

B. Modeling of RGB LED Luminaire G_{LED}

RGB LED luminaire is a lighting fixture assembling multiple RGB LED lamps on a common heatsink. The RGB LED lamp is an electrical device, packaging red, green, and blue LED chips, driven by electrical powers for diverse color LEDs individually. According to the law of energy conservation, LEDs emit photons and simultaneously generate heat when electrical powers are applied. Photon emission will generate a spectrum, i.e., spectral power distribution (SPD), to produce luminous and color perception [16]. The heat will raise the junction temperature, which leads to low quantum efficiency [17], spectral shift of SPD [17], and current droop [18], [19], to cause color drift and luminous intensity droop.

In this study, the total luminous intensity output Φ_{OUT} and chromaticity coordinates outputs in CIE 1976 UCS diagram $[u'_{OUT}, v'_{OUT}]^T$ were both chosen as outputs of RGB LED luminaire as follows:

$$\begin{bmatrix} \tilde{\Phi}_{OUT}(s) \\ \tilde{u}'_{OUT}(s) \\ \tilde{v}'_{OUT}(s) \end{bmatrix} = G_{LED}(s) \cdot \tilde{P}_{LED}(s) \quad (1)$$

where G_{LED} is the RGB LED luminaire model, $P_{LED} = [P_R \ P_G \ P_B]^T$ is the electrical power of RGB LEDs, in which the subscripts “ R ,” “ G ,” and “ B ,” respectively, represent the “red,” “green,” and “blue” components of signal; and “ $\sim$ ” represents perturbation. G_{LED} is a thermal–electrical–luminous–

Fig. 2. Block diagram of thermal–electrical–luminous–chromatic model of RGB LED luminaire.

chromatic model, as shown in Fig. 2, as follows:

$$G_{LED}(s) = \begin{bmatrix} U_E \cdot (E_P + E_T \cdot H(s)) \\ U_Y \cdot (Y_P + Y_T \cdot H(s)) \end{bmatrix} \quad (2)$$

and can be divided into five perturbed submodels: electrical–thermal (E-T) model H represents thermal dynamics of luminaire; thermal–luminous (T-L) model E_T and thermal–chromatic (T-C) model Y_T represent the opto-thermal effect; and electrical–luminous (E-L) model E_P and electrical–chromatic (E-C) model Y_P represent the opto-electrical effect. $U_E = [1 \ 1 \ 1]$ is the luminous summation unit, and $U_Y = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix}$ is the chromatic summation unit. Referring to the derivation of [15] and [20]–[22], the total luminous intensity output is derived as follows:

$$\begin{aligned} \tilde{\Phi}_{OUT}(s) &= U_E \cdot \tilde{\Phi}_{LED}(s) = U_E \cdot (\tilde{\Phi}_P(s) + \tilde{\Phi}_T(s)) \\ &= U_E \cdot (E_P \cdot \tilde{P}_{LED}(s) + E_T \cdot \tilde{T}_{LED}(s)) \\ &= U_E \cdot (E_P + E_T \cdot H(s)) \cdot \tilde{P}_{LED}(s) \\ &= U_E \cdot G_E(s) \cdot \tilde{P}_{LED}(s) \end{aligned} \quad (3)$$

where G_E is the luminous model, $\Phi_{LED} = [\Phi_R \ \Phi_G \ \Phi_B]^T$ is the luminous intensity of RGB LEDs, $T_{LED} = [T_R \ T_G \ T_B]^T$ is the junction temperature of RGB LEDs. All H , E_P , and E_T are derived by the input–output relation as follows, respectively:

$$\begin{aligned} H(s) &= \begin{bmatrix} H_{RR}(s) & H_{GR}(s) & H_{BR}(s) \\ H_{RG}(s) & H_{GG}(s) & H_{BG}(s) \\ H_{RB}(s) & H_{GB}(s) & H_{BB}(s) \end{bmatrix} \\ &= \begin{bmatrix} \tilde{T}_R(s)/\tilde{P}_R(s) & \tilde{T}_R(s)/\tilde{P}_G(s) & \tilde{T}_R(s)/\tilde{P}_B(s) \\ \tilde{T}_G(s)/\tilde{P}_R(s) & \tilde{T}_G(s)/\tilde{P}_G(s) & \tilde{T}_G(s)/\tilde{P}_B(s) \\ \tilde{T}_B(s)/\tilde{P}_R(s) & \tilde{T}_B(s)/\tilde{P}_G(s) & \tilde{T}_B(s)/\tilde{P}_B(s) \end{bmatrix} \\ &\quad \text{at } \tilde{T}_a \approx 0 \end{aligned} \quad (4)$$

$$\begin{aligned} E_T(s) &= \begin{bmatrix} E_{TR} & 0 & 0 \\ 0 & E_{TG} & 0 \\ 0 & 0 & E_{TB} \end{bmatrix} \\ &= \begin{bmatrix} \tilde{\Phi}_R(s)/\tilde{T}_R(s) & 0 & 0 \\ 0 & \tilde{\Phi}_G(s)/\tilde{T}_G(s) & 0 \\ 0 & 0 & \tilde{\Phi}_B(s)/\tilde{T}_B(s) \end{bmatrix} \end{aligned} \quad (5)$$

$$E_P(s) = \begin{bmatrix} E_{PR} & 0 & 0 \\ 0 & E_{PG} & 0 \\ 0 & 0 & E_{PB} \end{bmatrix} = \begin{bmatrix} \tilde{\Phi}_R(s)/\tilde{P}_R(s) & 0 & 0 \\ 0 & \tilde{\Phi}_G(s)/\tilde{P}_G(s) & 0 \\ 0 & 0 & \tilde{\Phi}_B(s)/\tilde{P}_B(s) \end{bmatrix}. \quad (6)$$

Due to the same phenomenon of opto-electrical and opto-thermal effects, the dynamics of luminous responses can be extended to chromatic responses. The chromaticity coordinates outputs are similarly derived as follows:

$$\begin{aligned} \begin{bmatrix} \tilde{u}'_{OUT}(s) \\ \tilde{v}'_{OUT}(s) \end{bmatrix} &= \begin{bmatrix} \tilde{u}'_P(s) \\ \tilde{v}'_P(s) \end{bmatrix} + \begin{bmatrix} \tilde{u}'_T(s) \\ \tilde{v}'_T(s) \end{bmatrix} \\ &= (U_Y \cdot Y_P \cdot \tilde{P}_{LED}(s) + U_Y \cdot Y_T \cdot \tilde{T}_{LED}(s)) \\ &= U_Y \cdot (Y_P + Y_T \cdot H(s)) \cdot \tilde{P}_{LED}(s) \\ &= U_Y \cdot G_Y(s) \cdot \tilde{P}_{LED}(s) \end{aligned} \quad (7)$$

where G_Y is the chromatic model and the subscripts “ P ” and “ T ” represent the effects of “electrical power” and “junction temperature,” respectively.

Both Y_P and Y_T , are derived by the input–output relation as well. First, the T-C model Y_T represents the influence on chromaticity coordinates of junction temperature as follows:

$$\begin{bmatrix} \tilde{u}'_T(s) \\ \tilde{v}'_T(s) \end{bmatrix} = U_Y \cdot Y_T(s) \cdot \tilde{T}_{LED}(s). \quad (8)$$

Similar to the deviation of E_T , Y_T is of zeroth order with a constant gain, defined in terms of linear perturbation concept as a 6×3 transfer function:

$$Y_T = \begin{bmatrix} Y_{Tu} \\ Y_{Tv} \end{bmatrix} = \begin{bmatrix} Y_{TuR} & 0 & 0 \\ 0 & Y_{TuG} & 0 \\ 0 & 0 & Y_{TuB} \\ Y_{TvR} & 0 & 0 \\ 0 & Y_{TvG} & 0 \\ 0 & 0 & Y_{TvB} \end{bmatrix} = \begin{bmatrix} \tilde{u}'_R(s)/\tilde{T}_R(s) & 0 & 0 \\ 0 & \tilde{u}'_G(s)/\tilde{T}_G(s) & 0 \\ 0 & 0 & \tilde{u}'_B(s)/\tilde{T}_B(s) \\ \tilde{v}'_R(s)/\tilde{T}_R(s) & 0 & 0 \\ 0 & \tilde{v}'_G(s)/\tilde{T}_G(s) & 0 \\ 0 & 0 & \tilde{v}'_B(s)/\tilde{T}_B(s) \end{bmatrix} \quad (9)$$

where the Y_T further divides into two diagonal 3×3 submodels Y_{Tu} and Y_{Tv} to represent the responses of the u' -coordinate and v' -coordinate, respectively. Second, the E-C model Y_P represents the influence on chromaticity coordinates of electrical

power as follows:

$$\begin{bmatrix} \tilde{u}'_P(s) \\ \tilde{v}'_P(s) \end{bmatrix} = U_Y \cdot Y_P(s) \cdot \tilde{P}_{LED}(s). \quad (10)$$

Similarly, Y_P is of zeroth order with a constant gain, defined in terms of linear perturbation concept as a 6×3 transfer function:

$$Y_P = \begin{bmatrix} Y_{Pu} \\ Y_{Pv} \end{bmatrix} = \begin{bmatrix} Y_{PuR} & 0 & 0 \\ 0 & Y_{PuG} & 0 \\ 0 & 0 & Y_{PuB} \\ Y_{PvR} & 0 & 0 \\ 0 & Y_{PvG} & 0 \\ 0 & 0 & Y_{PvB} \end{bmatrix} = \begin{bmatrix} \tilde{u}'_R(s)/\tilde{P}_R(s) & 0 & 0 \\ 0 & \tilde{u}'_G(s)/\tilde{P}_G(s) & 0 \\ 0 & 0 & \tilde{u}'_B(s)/\tilde{P}_B(s) \\ \tilde{v}'_R(s)/\tilde{P}_R(s) & 0 & 0 \\ 0 & \tilde{v}'_G(s)/\tilde{P}_G(s) & 0 \\ 0 & 0 & \tilde{v}'_B(s)/\tilde{P}_B(s) \end{bmatrix} \quad (11)$$

where the E-C model Y_P divides into two 3×3 submodels Y_{Pu} and Y_{Pv} , the same as in the Y_T .

In addition, the chromatic transformer F represents a mapping from the chromaticity coordinate outputs $[u'_{OUT}, v'_{OUT}]^T$ onto CCT output $T_{CC,OUT}$. According to [23] and [24], CCT is obtained from a nonlinear approach as follows:

$$F : \begin{cases} T_{CC,OUT} = 449n^3 + 3525n^2 + 6823.3n + 5520.3 \\ n = \frac{x - 0.332}{0.1858 - y} \\ x = \frac{9u'_{OUT}}{6u'_{OUT} - 16v'_{OUT} + 12} \\ y = \frac{4v'_{OUT}}{6u'_{OUT} - 16v'_{OUT} + 12} \end{cases} \quad (12)$$

where n is the converting operator, and x and y are the chromaticity coordinates in CIE 1931 diagram.

C. Modeling of Converter N

Converter N carries out a conversion to transform from the input commands of $T_{CC,r}$ and Φ_r , to three corresponding control signals: converted radiant power L_A , converted electrical power P_A , and converted junction temperature T_A ; these five parameters were interdependent. The N is described as follows:

$$(L_A, T_A, P_A) = N(T_{CC,r}, \Phi_r). \quad (13)$$

The N must be consistent with the dynamics of RGB LED luminaire; therefore, N is obtained from a set of experimental data of RGB LED luminaire, i.e., $T_{CC,OUT}$, Φ_{OUT} , L_S , P_{LED} , and T_{LED} , to construct the (13). Furthermore, N could divide into three identical submodels when the set of experimental data

Fig. 3. Block diagram of converter N . Fig. 4. Block diagram of compensator M .

is interdependent, described as follows:

$$N: \begin{cases} L_A = N_L(T_{CC,r}, \Phi_r) \\ T_A = N_T(T_{CC,r}, \Phi_r) \\ P_A = N_P(T_{CC,r}, \Phi_r) \end{cases} \quad (14)$$

where N_L is the radiant converter, N_T is the temperature converter, and N_P is the electrical converter. Its detailed block diagram is shown in Fig. 3.

D. Modeling of Compensator M

M is a feed-forward compensator, producing radiant compensation L_M , compensating the color drift and luminous intensity droop during the entire operating period due to junction temperature rise, and adjusting the signal mismatch between the converter N outputs and initial responses of RGB LEDs for junction temperature and electrical power. M consists of three submodels: temperature-compensator M_T , initial-temperature-compensator W_T , and initial-electrical-compensator W_P , as shown in Fig. 4. The output of compensator L_M is described as follows:

$$\begin{aligned} \tilde{L}_M(s) &= \tilde{L}_T(s) + \Delta L_{IT} + \Delta L_{IP} \\ &= M_T(s) \cdot \tilde{T}_{LED}(s) + W_T \cdot \Delta T_I + W_P \cdot \Delta P_I. \end{aligned} \quad (15)$$

where L_T is the feed-forward compensation, ΔL_{IT} the radiant difference of temperature, ΔL_{IP} the radiant difference of electrical power, ΔT_I the initial temperature difference defined the difference between converted junction temperature T_A , and initial junction temperature of RGB LEDs $T_{LED,0}$, i.e., $\Delta T_I = T_A - T_{LED,0}$. Similarly, the initial power difference is defined as $\Delta P_I = P_A - P_{LED,0}$.

The three submodels are derived by the input–output relation. First, temperature compensator M_T represents the influence on feed-forward compensation L_T of junction temperature T_{LED}

as follows:

$$\tilde{L}_T(s) = M_T(s) \cdot \tilde{T}_{LED}(s) \quad (16)$$

and is defined as a perturbed model as

$$\begin{aligned} M_T(s) &= \begin{bmatrix} N_{RR}(s) & N_{GR}(s) & N_{BR}(s) \\ N_{RG}(s) & N_{GG}(s) & N_{BG}(s) \\ N_{RB}(s) & N_{GB}(s) & N_{BB}(s) \end{bmatrix} \\ &= \begin{bmatrix} \tilde{L}_{TR}(s)/\tilde{T}_R(s) & \tilde{L}_{TR}(s)/\tilde{T}_G(s) & \tilde{L}_{TR}(s)/\tilde{T}_B(s) \\ \tilde{L}_{TG}(s)/\tilde{T}_R(s) & \tilde{L}_{TG}(s)/\tilde{T}_G(s) & \tilde{L}_{TG}(s)/\tilde{T}_B(s) \\ \tilde{L}_{TB}(s)/\tilde{T}_R(s) & \tilde{L}_{TB}(s)/\tilde{T}_G(s) & \tilde{L}_{TB}(s)/\tilde{T}_B(s) \end{bmatrix}. \end{aligned} \quad (17)$$

Second, initial-temperature-compensator W_T and initial-electrical-compensator W_P represent the radiant difference by initial temperature difference ΔT_I and initial electrical power difference ΔP_I , respectively, as follows, respectively:

$$\Delta L_{IT} = W_T \cdot \Delta T_I \quad (18)$$

$$\Delta L_{IP} = W_P \cdot \Delta P_I. \quad (19)$$

The W_T and W_P are defined as follows, respectively:

$$\begin{aligned} W_T &= \begin{bmatrix} W_{TRR} & W_{TGR} & W_{TBR} \\ W_{TRG} & W_{TGG} & W_{TBG} \\ W_{TRB} & W_{TGB} & W_{TBB} \end{bmatrix} \\ &= \begin{bmatrix} \Delta L_{ITR}/\Delta T_{IR} & \Delta L_{ITR}/\Delta T_{IG} & \Delta L_{ITR}/\Delta T_{IB} \\ \Delta L_{ITG}/\Delta T_{IR} & \Delta L_{ITG}/\Delta T_{IG} & \Delta L_{ITG}/\Delta T_{IB} \\ \Delta L_{ITB}/\Delta T_{IR} & \Delta L_{ITB}/\Delta T_{IG} & \Delta L_{ITB}/\Delta T_{IB} \end{bmatrix} \end{aligned} \quad (20)$$

$$\begin{aligned} W_P &= \begin{bmatrix} W_{PRR} & W_{PGR} & W_{PBR} \\ W_{PRG} & W_{PGG} & W_{PBG} \\ W_{PRB} & W_{PGB} & W_{PBB} \end{bmatrix} \\ &= \begin{bmatrix} \Delta L_{IPR}/\Delta P_{IR} & \Delta L_{IPR}/\Delta P_{IG} & \Delta L_{IPR}/\Delta P_{IB} \\ \Delta L_{IPG}/\Delta P_{IR} & \Delta L_{IPG}/\Delta P_{IG} & \Delta L_{IPG}/\Delta P_{IB} \\ \Delta L_{IPB}/\Delta P_{IR} & \Delta L_{IPB}/\Delta P_{IG} & \Delta L_{IPB}/\Delta P_{IB} \end{bmatrix}. \end{aligned} \quad (21)$$

The model of M must be consistent with the dynamics of RGB LED luminaire; for the functions of M is including the modification for Φ_{LED} and $[u'_{OUT}, v'_{OUT}]^T$ due to junction temperature rise, and adjustment of signal mismatch between the outputs of converter N and initial responses of RGB LEDs. Therefore, the M can be derived from RGB LED luminaire models as mentioned previously, that is, E_P , E_T , Y_P , and Y_T . The detailed derivation is discussed in next section.

III. SYSTEM IDENTIFICATION

A. Experimental Setup

In this study, an RGB LED luminaire [21] was set up for system identification and lighting control; it is assembled by five RGB LED lamps [25] with a joint 900 g aluminum heatsink.

Fig. 5. Illustration of driver design for red LEDs.

TABLE I
ELECTRICAL POWER CONDITIONS OF RGB LED LUMINAIRE FOR WHITE
LIGHT GENERATION

CCT	3,500K				6,000K				8,000K			
(u', v')	(0.2346, 0.5114)				(0.2032, 0.4708)				(0.1951, 0.4519)			
Electrical power, P_{LED} (%)	NO.	P_R	P_G	P_B	NO.	P_R	P_G	P_B	NO.	P_R	P_G	P_B
	1	89.0	25.7	12.0	4	87.0	32.0	27.0	7	85.4	33.2	35.0
	2	77.5	22.1	11.5	5	71.0	26.2	22.0	8	68.8	26.9	28.0
	3	60.4	17.8	8.5	6	50.8	18.8	16.0	9	49.6	19.5	20.0

Four lamps were installed in front of the luminaire for lighting and the fifth lamp with an Si photodiode [26] as the LED sensor was set inside the luminaire to measure junction temperature T_{LED} and radiant power L_S of RGB LEDs.

Three color LEDs were independently driven by three drivers, as shown in Fig. 5, which were connected to identical color LEDs of five lamps in series connection. The three drivers independently produced direct current pulsewidth modulation (DCPWM) outputs. The ON/OFF current levels were supplied at 350 mA/1 mA, and the switching frequencies were fixed 120 Hz to avoid flicking perception [27]. The maximum electrical power in a single RGB LED lamp is $P_{LED, max} = [121 \ 2.56 \ 1.27]^T \text{ W} \equiv [100 \ 100 \ 100]^T \%$, described in watt or percentage (%), where the power levels are proportionally manipulated by duty cycle. The unit of electrical power is thus defined as “%.” The electrical power conditions of three CCTs, i.e., 3500, 6000, and 8000 K, are listed in Table I for the following experiments. A thermal pad was attached to the luminaire to introduce extra thermal disturbance. By using the forward voltage method [28]–[30], the T_{LED} were estimated by measuring the average forward voltage of the LED sensor, $V_{LOW} = [V_{TR} \ V_{TG} \ V_{TB}]^T$, while 1 mA constant current were applied during the OFF period of DCPWM, as follows:

$$T_{LED} = S_T \cdot V_{LOW} \quad (22)$$

where S_T is the temperature sensitive parameter obtained from the calibration experiment by 1 mA constant current pulse with

Fig. 6. Voltage responses of RGB LEDs and Si photodiode within one period.

50 μs pulsewidth, as follows [15]:

$$S_T = \begin{bmatrix} S_{TR} & 0 & 0 \\ 0 & S_{TG} & 0 \\ 0 & 0 & S_{TB} \end{bmatrix} = \begin{bmatrix} 1.82 & 0 & 0 \\ 0 & 5.90 & 0 \\ 0 & 0 & 2.20 \end{bmatrix} \times 10^{-3}. \quad (23)$$

The luminous intensity of RGB LEDs Φ_{LED} can be obtained by measuring the radiant powers $L_S = [L_R \ L_G \ L_B]^T$ as follows:

$$L_S = S_D \cdot \Phi_{LED}. \quad (24)$$

The luminous detector model S_D was then obtained by experimental calibration [15] as

$$S_D = \begin{bmatrix} S_{DR} & 0 & 0 \\ 0 & S_{DG} & 0 \\ 0 & 0 & S_{DB} \end{bmatrix} = \begin{bmatrix} 0.0287 & 0 & 0 \\ 0 & 0.0212 & 0 \\ 0 & 0 & 0.1077 \end{bmatrix}. \quad (25)$$

Hence, the luminous intensity Φ_{LED} can be measured directly and individually.

The radiant powers L_S was measured by the LED sensor, i.e., the fifth lamp with an Si photodiode. The procedures were arranged as follows [4]. First, it is designed that the three DCPWM outputs were synchronous and their negative slope edge were occurred sequentially. The order was set red, green, and blue LEDs in turn, and the each time intervals of signals were set 2% duty cycle, i.e., 166.66 μs . The voltage responses of DCPWMs and Si photodiode are shown in Fig. 6. Second, the voltage falling edge of red LEDs was set as reference point to trigger the voltage measurement of Si photodiode at three specific time points, i.e., 1%, 3%, and 99% duty cycle delayed to reference point. Its corresponding voltage values are equal to $V_{S,1} = V_{SG} + V_{SB}$, $V_{S,3} = V_{SB}$, and $V_{S,99} = V_{SR} + V_{SG} + V_{SB}$, respectively, where V_{SR} , V_{SG} , and V_{SB} are Si photodiode sensed voltage of red, green, and blue LEDs. Third, the sensed voltages

of RGB LEDs are decoupled as follows:

$$\begin{aligned} \begin{bmatrix} V_{S,1} \\ V_{S,3} \\ V_{S,99} \end{bmatrix} &= \begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} V_{SR} \\ V_{SG} \\ V_{SB} \end{bmatrix} \\ \Rightarrow \begin{bmatrix} V_{SR} \\ V_{SG} \\ V_{SB} \end{bmatrix} &= \begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix}^{-1} \cdot \begin{bmatrix} V_{S,1} \\ V_{S,3} \\ V_{S,99} \end{bmatrix} \\ &= \begin{bmatrix} V_{S,99} - V_{S,1} \\ V_{S,1} - V_{S,3} \\ V_{S,3} \end{bmatrix}. \end{aligned} \quad (26)$$

Finally, the radiant powers L_S is obtained as follows:

$$L_S = \begin{bmatrix} L_R \\ L_G \\ L_B \end{bmatrix} = \begin{bmatrix} D_{CR} \cdot V_{SR} \\ D_{CG} \cdot V_{SG} \\ D_{CB} \cdot V_{SB} \end{bmatrix} \quad (27)$$

where D_{CR} , D_{CG} , and D_{CB} are the duty cycles of red, green, and blue LEDs, respectively.

For identification, a set of testing apparatuses, the same as [15] (see Fig. 6), was installed to acquire total luminous intensity output Φ_{OUT} , chromaticity coordinate outputs $[u'_{OUT}, v'_{OUT}]^T$, and CCT output $T_{CC,OUT}$. Moreover, the calculation of $[u'_{OUT}, v'_{OUT}]^T$ was obtained as follows [23]:

$$\begin{aligned} \begin{bmatrix} u'_{OUT} \\ v'_{OUT} \end{bmatrix} &= \begin{bmatrix} 4X/(X+15Y+3Z) \\ 9Y/(X+15Y+3Z) \end{bmatrix} = CT(D), \\ \text{where } \begin{cases} X = \int_{380}^{780} D \cdot \bar{x} \cdot d\lambda \\ Y = \int_{380}^{780} D \cdot \bar{y} \cdot d\lambda \\ Z = \int_{380}^{780} D \cdot \bar{z} \cdot d\lambda \end{cases} \end{aligned} \quad (28)$$

where D is the SPD of RGB LEDs; $\bar{x}$, $\bar{y}$ and $\bar{z}$ are the color matching function; and X , Y and Z are the tristimulus values.

B. Identification of RGB LED Luminaire G_{LED}

The five submodels of G_{LED} carried out system identification individually. First, the E-T model H was obtained from (4) and is shown in [15], [20], and [21]. Second, the T-L model E_T and the T-E model E_P were obtained from (5) and (6), respectively, and the both models were identified as constant gain in [15] and [21]. Furthermore, the model of E_T is observed as linearly electrical-dependent (see Fig. 7); in other words, the E_T is different from and linear to diverse electrical power conditions. In order to simplify the model description among operating range, E_T can be characterized as follows:

$$\begin{aligned} E_T &= E_T(P_{LED}) \\ &= \begin{bmatrix} -0.139 & 0 & 0 \\ 0 & -0.151 & 0 \\ 0 & 0 & -0.012 \end{bmatrix} \cdot \begin{bmatrix} P_R \\ P_G \\ P_B \end{bmatrix} \end{aligned}$$

Fig. 7. Relations of thermal-luminous model E_T and electrical power of RGB LEDs P_{LED} .

Fig. 8. Relations of electrical-luminous model E_P and junction temperature of RGB LEDs T_{LED} .

$$+ \begin{bmatrix} -0.369 & 0 & 0 \\ 0 & -0.661 & 0 \\ 0 & 0 & -0.251 \end{bmatrix}. \quad (29)$$

Similarly, the model of E_P was observed as linearly temperature-dependent (see Fig. 8) as well.

$$\begin{aligned} E_P &= E_P(T_{LED}) \\ &= \begin{bmatrix} -0.139 & 0 & 0 \\ 0 & -0.125 & 0 \\ 0 & 0 & -0.012 \end{bmatrix} \cdot \begin{bmatrix} T_R \\ T_G \\ T_B \end{bmatrix} \\ &+ \begin{bmatrix} 25.26 & 0 & 0 \\ 0 & 76.72 & 0 \\ 0 & 0 & 11.00 \end{bmatrix}. \end{aligned} \quad (30)$$

Third, the T-C model Y_T was obtained from (9) and identified as a constant gain by linear regression. The P_{LED} were set constant, in turn, of the operating conditions given in Table I in the experiment. Accordingly, the T_{LED} was determined by self-heating and thermal interaction among three color LEDs. The T_{LED} rise would cause SPD variation of three color LEDs, respectively. In order to decouple the chromatic responses of the three color LEDs, the SPDs of RGB LEDs were thus defined as

Fig. 9. u' -coordinate experimental responses of thermal-chromatic model Y_{Tu} at CCT 6000 K. (a) u' -coordinate responses of red LEDs. (b) Relations of Y_{Tu} and P_{LED} .

follows:

$$\begin{cases} \text{SPD of red LEDs: } D_R = D|_{\lambda_1}^{780 \text{ nm}} \\ \text{SPD of green LEDs: } D_G = D|_{\lambda_2}^{\lambda_1} \\ \text{SPD of blue LEDs: } D_B = D|_{380 \text{ nm}}^{\lambda_2} \end{cases} \quad (31)$$

where λ_1 is the wavelength of the spectrum trough between blue and green LEDs and λ_2 is the wavelength of the spectrum trough between green and red LEDs. Referring to (28), the perturbations of $[u'_T, v'_T]^T$ influenced by junction temperature of single-color LEDs were calculated from

$$\begin{bmatrix} \tilde{u}'_T \\ \tilde{v}'_T \end{bmatrix} = CT(\bar{D} + \tilde{D}_i) - CT(\bar{D}), \text{ for } \tilde{T}_i, \text{ where } i = R, G, B. \quad (32)$$

The modeling of u' -coordinate T-C model for the red LEDs Y_{TuR} at CCT 6000 K are shown in Fig. 9(a). Furthermore, Y_T is observed as linearly electrical-dependent. In the example of CCT 6000 K, the u' -coordinate T-C model Y_{Tu} was depicted as

a linear function of P_{LED} [see Fig. 9(b)] as follows:

$$Y_T = Y_T(P_{LED}) = \begin{bmatrix} 1.485 & 0 & 0 \\ 0 & 0.730 & 0 \\ 0 & 0 & 0.188 \\ 0.495 & 0 & 0 \\ 0 & -0.377 & 0 \\ 0 & 0 & -1.009 \end{bmatrix} \times 10^{-6} \cdot P_{LED} + \begin{bmatrix} -8.046 & 0 & 0 \\ 0 & 1.821 & 0 \\ 0 & 0 & -0.110 \\ -1.947 & 0 & 0 \\ 0 & -1.171 & 0 \\ 0 & 0 & 2.981 \end{bmatrix} \times 10^{-4}. \quad (33)$$

Fourth, the E-C model Y_P was obtained from (11) and identified as a constant gain by linear regression. The P_{LED} were first set constant, in turn, of the operating conditions given in Table I in the experiment. Additionally, P_{LED} were applied, in turn, extra perturbations of $\tilde{P}_R = \pm 2.0\%$, $\tilde{P}_G = \pm 1.5\%$, and $\tilde{P}_B = \pm 1.0\%$ with five divisions, individually. The extra perturbations are small enough to hold the chromaticity coordinates approximately remained at designing CCT. The perturbations of electrical powers were calculated from (28) as follows:

$$\begin{aligned} \begin{bmatrix} \tilde{u}'_P \\ \tilde{v}'_P \end{bmatrix} &= \begin{bmatrix} \tilde{u}'_{OUT} \\ \tilde{v}'_{OUT} \end{bmatrix} - \begin{bmatrix} \tilde{u}'_T \\ \tilde{v}'_T \end{bmatrix} \\ &= (CT(\bar{D} + \tilde{D}_i) - CT(\bar{D})) - U_Y \cdot Y_T \cdot \tilde{T}_{LED}, \\ &\text{for } \tilde{P}_i, \text{ where } i = R, G, B. \end{aligned} \quad (34)$$

The modeling of u' -coordinate E-C model for the red LEDs Y_{PuR} at CCT 6000 K are shown in Fig. 10(a). Furthermore, Y_P is observed as linearly electrical-dependent. In the example of CCT 6000 K, the u' -coordinate E-C model Y_{Pu} was depicted as a linear function of P_{LED} [see Fig. 10(b)] as follows:

$$Y_P = Y_P(P_{LED}) = \begin{bmatrix} -0.259 & 0 & 0 \\ 0 & 1.927 & 0 \\ 0 & 0 & 0.326 \\ -0.054 & 0 & 0 \\ 0 & -1.307 & 0 \\ 0 & 0 & 2.245 \end{bmatrix} \times 10^{-4} \cdot P_{LED} + \begin{bmatrix} 3.271 & 0 & 0 \\ 0 & -8.871 & 0 \\ 0 & 0 & 1.235 \\ 0.659 & 0 & 0 \\ 0 & 5.962 & 0 \\ 0 & 0 & -8.791 \end{bmatrix} \times 10^{-3}. \quad (35)$$

Fig. 10. u' -coordinate experimental responses of electrical-chromatic model Y_{Pu} at CCT 6000 K. (a) u' -coordinate responses of red LEDs. (b) Relations of Y_{Pu} and P_{LED} .

C. Identification of Converter N

The converter N represents the transmission path from CCT command $T_{CC,r}$ and total luminous intensity command Φ_r to converted junction temperature T_A , converted electrical power P_A , and converted radiant power L_A . The three submodels N_L , N_P , and N_T were carried out with curve-fitting technique, individually, by using the interdependent responses of the T-C model identification, i.e., $T_{CC,OUT}$, Φ_{OUT} , T_{LED} , P_{LED} , and L_S . In the example of N_L , L_A can be obtained from the relations among $T_{CC,OUT}$, Φ_{OUT} , and L_S according to (37). The identification consists of three steps: First, the Φ_{OUT} of three CCTs are overlapping and can be fitted as a single linear function of the radiant power of green LED L_G , as shown in Fig. 11(a). Second, normalized radiant power L_N is defined as follows:

$$L_N = \begin{bmatrix} L_{NR} \\ L_{NG} \\ L_{NB} \end{bmatrix} = \begin{bmatrix} L_R / (L_R + L_G + L_B) \\ L_G / (L_R + L_G + L_B) \\ L_B / (L_R + L_G + L_B) \end{bmatrix}. \quad (36)$$

The ratio of three elements of L_N is constant to Φ_{OUT} , as depicted in Fig. 11(b). Third, the $T_{CC,OUT}$ are linear to L_N , as shown in Fig. 11(c). Combining these three relations, N_L is obtained as follows:

$$N_L: L_A \equiv L_S = L_N \cdot \frac{L_{AG}}{L_{NG}} = \begin{bmatrix} L_{NR} \\ L_{NG} \\ L_{NB} \end{bmatrix} \cdot \frac{L_{AG}}{L_{NG}},$$

Fig. 11. Experimental responses for identification of radiant-converter N_L . (a) Φ_{OUT} versus L_G . (b) Φ_{OUT} versus L_N at CCT 3500 K. (c) $T_{CC,OUT}$ versus L_N .

$$\text{where } \begin{cases} L_{AG} = 0.01197 \Phi_r - 0.4440 \\ L_{NR} = -2.963e^{-5} \cdot T_{CC,r} + 0.585 \\ L_{NG} = -2.164e^{-6} \cdot T_{CC,r} + 0.387 \\ L_{NB} = 3.180e^{-5} \cdot T_{CC,r} + 0.0028 \end{cases} \quad (37)$$

Similarly, the same analytical technique was applied for identification of N_P and N_T . N_P and the N_T are given by,

respectively,

$$N_P: P_A \equiv P_{LED} = P_N \cdot \frac{P_{AG}}{P_{NG}} = \begin{bmatrix} P_{NR} \\ P_{NG} \\ P_{NB} \end{bmatrix} \cdot \frac{P_{AG}}{P_{NG}},$$

$$\text{where} \begin{cases} P_{AG} = 7.678 e^{-3} \Phi_r - 0.386 \\ P_{RN} = -3.174 e^{-5} \cdot T_{CC,r} + 0.801 \\ P_{GN} = 3.459 e^{-6} \cdot T_{CC,r} + 0.195 \\ P_{BN} = 2.828 e^{-5} \cdot T_{CC,r} + 0.0004 \end{cases} \quad (38)$$

$$N_T: T_A \equiv T_{LED} = T_N \cdot \frac{T_{AG}}{T_{NG}} = \begin{bmatrix} T_{NR} \\ T_{NG} \\ T_{NB} \end{bmatrix} \cdot \frac{T_{AG}}{T_{NG}},$$

$$\text{where} \begin{cases} T_{AG} = 2.580 e^{-3} \Phi_r + 36.38 \\ T_{NR} = -1.346 e^{-6} \cdot T_{CC,r} + 0.350 \\ T_{NG} = -7.156 e^{-7} \cdot T_{CC,r} + 0.333 \\ T_{NB} = 2.062 e^{-6} \cdot T_{CC,r} + 0.317 \end{cases} \quad (39)$$

where P_N is the normalized electrical power and T_N is the normalized junction temperature.

D. Derivation of Compensator M

The compensator M produced radiant compensation L_M by using initial temperature difference ΔT_I and initial electrical power difference ΔP_I ; in addition, M must be consistent with the dynamics of RGB LED luminaire to compensate the color drift and luminous intensity droop. Therefore, we constructed a combined relation of T_{LED} , P_{LED} , L_S , Φ_{OUT} , u'_{OUT} , and v'_{OUT} in advance. The combined relation sets the difference of Φ_{OUT} , u'_{OUT} , and v'_{OUT} equal to zero and then transforms into M . M can produce radiant compensation L_M to modify radiant command L_C according to the dynamics of RGB LED luminaire. Eventually, a proper L_C set as reference can guar-

antee luminous and chromatic stability by using the FFB loop control, as shown in Fig. 1.

The combined relation is solved by using the identified models as mentioned previously, i.e., E_P , E_T , Y_P , and Y_T . First, combining (3) and (24), Φ_{LED} is given by

$$\tilde{\Phi}_{LED}(s) = S_D^{-1} \cdot \tilde{L}_S(s) = E_P \cdot \tilde{P}_{LED}(s) + E_T \cdot \tilde{T}_{LED}(s)$$

then

$$\tilde{P}_{LED}(s) = (E_P^{-1} \cdot S_D^{-1}) \cdot \tilde{L}_S(s) - (E_P^{-1} \cdot E_T) \cdot \tilde{T}_{LED}(s). \quad (40)$$

We capture the u' -coordinate and v' -coordinate models of (9) and (11), i.e., Y_{Pu} , Y_{Pv} , Y_{Tu} , and Y_{Tv} . Their relations are reconstructed by (40) as follows:

$$\begin{bmatrix} \tilde{u}'_R(s) \\ \tilde{u}'_G(s) \\ \tilde{u}'_B(s) \end{bmatrix} = Y_{Pu} \cdot \tilde{P}_{LED}(s) + Y_{Tu} \cdot \tilde{T}_{LED}(s) \\ = (Y_{Pu} \cdot E_P^{-1} \cdot S_D^{-1}) \cdot \tilde{L}_S(s) \\ + (Y_{Tu} - Y_{Pu} \cdot (E_P^{-1} \cdot E_T)) \cdot \tilde{T}_{LED}(s). \quad (41)$$

$$\begin{bmatrix} \tilde{v}'_R(s) \\ \tilde{v}'_G(s) \\ \tilde{v}'_B(s) \end{bmatrix} = (Y_{Pv} \cdot E_P^{-1} \cdot S_D^{-1}) \cdot \tilde{L}_S(s) \\ + (Y_{Tv} - Y_{Pv} \cdot (E_P^{-1} \cdot E_T)) \cdot \tilde{T}_{LED}(s). \quad (42)$$

Referring to the definition of (3) and (24), the total luminous intensity output Φ_{OUT} is described in

$$\tilde{\Phi}_{OUT} = U_E \cdot \tilde{\Phi}_{LED}(s) = U_E \cdot S_D^{-1} \cdot \tilde{L}_S(s). \quad (43)$$

Combining (41)–(43) and the definition of T_{LED} , u'_{OUT} , and v'_{OUT} into a 12×12 simultaneous equation yields the following, as shown (*), at the bottom of this page.

$$\begin{bmatrix} (Y_{Pu} \cdot E_D^{-1} \cdot S_D^{-1}) & (Y_{Tu} - Y_{Pu} \cdot (E_D^{-1} \cdot E_T)) & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ (Y_{Pv} \cdot E_D^{-1} \cdot S_D^{-1}) & (Y_{Tv} - Y_{Pv} \cdot (E_D^{-1} \cdot E_T)) & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ U_E \cdot S_D^{-1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{12 \times 12} \cdot \begin{bmatrix} \tilde{L}_S \\ \tilde{T}_{LED} \\ \tilde{u}'_R \\ \tilde{u}'_G \\ \tilde{u}'_B \\ \tilde{v}'_R \\ \tilde{v}'_G \\ \tilde{v}'_B \end{bmatrix}_{12 \times 1} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \tilde{\Phi}_{OUT} \\ \tilde{u}'_{OUT} \\ \tilde{v}'_{OUT} \end{bmatrix}_{12 \times 1}. \quad (*)$$

The solution is, as shown (44), at the bottom of the page.

Referring to (1), (3), and (7), the perturbation “ $\sim$ ” is redefined as difference “ Δ ” for the RGB LED luminaire outputs at the initial moment as follows:

$$\begin{bmatrix} \tilde{\Phi}_{OUT} \\ \tilde{u}'_{OUT} \\ \tilde{v}'_{OUT} \end{bmatrix} \triangleq \begin{bmatrix} \Delta \Phi_I \\ \Delta u'_I \\ \Delta v'_I \end{bmatrix} = \begin{bmatrix} U_E \cdot E_T \\ U_Y \cdot Y_T \end{bmatrix} \cdot \Delta T_I + \begin{bmatrix} U_E \cdot E_P \\ U_Y \cdot Y_P \end{bmatrix} \cdot \Delta P_I. \quad (45)$$

Substituting (45) into the upper three rows of (44), we get

$$\begin{aligned} \tilde{L}_S &= \begin{bmatrix} F_{7,1} & F_{8,1} & F_{9,1} \\ F_{7,2} & F_{8,2} & F_{9,2} \\ F_{7,3} & F_{8,3} & F_{9,3} \end{bmatrix} \cdot \tilde{T}_{LED} + \begin{bmatrix} F_{10,1} & F_{11,1} & F_{12,1} \\ F_{10,2} & F_{11,2} & F_{12,2} \\ F_{10,3} & F_{11,3} & F_{12,3} \end{bmatrix} \\ &\cdot \begin{bmatrix} \tilde{\Phi}_{OUT} \\ \tilde{u}'_{OUT} \\ \tilde{v}'_{OUT} \end{bmatrix} \\ &\equiv \begin{bmatrix} F_{7,1} & F_{8,1} & F_{9,1} \\ F_{7,2} & F_{8,2} & F_{9,2} \\ F_{7,3} & F_{8,3} & F_{9,3} \end{bmatrix} \cdot \tilde{T}_{LED} + \begin{bmatrix} F_{10,1} & F_{11,1} & F_{12,1} \\ F_{10,2} & F_{11,2} & F_{12,2} \\ F_{10,3} & F_{11,3} & F_{12,3} \end{bmatrix} \\ &\cdot \left(\begin{bmatrix} U_E \cdot E_T \\ U_Y \cdot Y_T \end{bmatrix} \cdot \Delta T_I + \begin{bmatrix} U_E \cdot E_P \\ U_Y \cdot Y_P \end{bmatrix} \cdot \Delta P_I \right). \quad (46) \end{aligned}$$

Referring to (15), the three sub-models of compensator, i.e., M_T , W_T , W_P , are modeled in comparison to (46) as follows:

$$M_T = \begin{bmatrix} F_{7,1} & F_{8,1} & F_{9,1} \\ F_{7,2} & F_{8,2} & F_{9,2} \\ F_{7,3} & F_{8,3} & F_{9,3} \end{bmatrix} \quad (47)$$

$$W_T = \begin{bmatrix} F_{10,1} & F_{11,1} & F_{12,1} \\ F_{10,2} & F_{11,2} & F_{12,2} \\ F_{10,3} & F_{11,3} & F_{12,3} \end{bmatrix} \cdot \begin{bmatrix} U_E \cdot E_T \\ U_Y \cdot Y_T \end{bmatrix} \quad (48)$$

Fig. 12. Block diagram of FFB loops for controller design. (a) FFB loop. (b) Decoupled red LED loop (Solid lines: scalar signals; mesh lines: vector signals).

$$W_P = \begin{bmatrix} F_{10,1} & F_{11,1} & F_{12,1} \\ F_{10,2} & F_{11,2} & F_{12,2} \\ F_{10,3} & F_{11,3} & F_{12,3} \end{bmatrix} \cdot \begin{bmatrix} U_E \cdot E_P \\ U_Y \cdot Y_P \end{bmatrix}. \quad (49)$$

Since M is derived by E_P , E_T , Y_P , and Y_T , which are electrical- or temperature-dependent, M will constantly vary during the entire operating period. Therefore, the three submodels of M , i.e., M_T , W_T , and W_P , must be remodeled in each control period.

IV. CONTROLLER DESIGN

Regarding the FFB&TFF structure shown in Fig. 1, it is noted that the performance of the RGB LED lighting control system is dominated mainly by the FFB loop if the converter N and compensator M provide exact radiant command L_C . Therefore, we segmented the FFB loop for the controller design, as depicted in Fig. 12(a). The plant of FFB loop G_{ES} is defined as the average luminous model G_{E0} with luminous detector model S_D , i.e., $G_{ES} = S_D \cdot G_{E0}$, where the G_{E0} is obtained by the

$$\Rightarrow \begin{bmatrix} \tilde{L}_S \\ \tilde{T}_{LED} \\ \tilde{u}'_R(s) \\ \tilde{u}'_G(s) \\ \tilde{u}'_B(s) \\ \tilde{v}'_R(s) \\ \tilde{v}'_G(s) \\ \tilde{v}'_B(s) \end{bmatrix}_{12 \times 1} = \begin{bmatrix} F_{1,1} & F_{2,1} & F_{3,1} & F_{4,1} & F_{5,1} & F_{6,1} & F_{7,1} & F_{8,1} & F_{9,1} & F_{10,1} & F_{11,1} & F_{12,1} \\ F_{1,2} & F_{2,2} & F_{3,2} & F_{4,2} & F_{5,2} & F_{6,2} & F_{7,2} & F_{8,2} & F_{9,2} & F_{10,2} & F_{11,2} & F_{12,2} \\ F_{1,3} & F_{2,3} & F_{3,3} & F_{4,3} & F_{5,3} & F_{6,3} & F_{7,3} & F_{8,3} & F_{9,3} & F_{10,3} & F_{11,3} & F_{12,3} \\ F_{1,4} & F_{2,4} & F_{3,4} & F_{4,4} & F_{5,4} & F_{6,4} & F_{7,4} & F_{8,4} & F_{9,4} & F_{10,4} & F_{11,4} & F_{12,4} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix}_{12 \times 12} \cdot \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \tilde{T}_{LED} \\ \tilde{\Phi}_{OUT} \\ \tilde{u}'_{OUT} \\ \tilde{v}'_{OUT} \end{bmatrix}_{12 \times 1}. \quad (44)$$

identification of H , E_P , and E_T .

$$G_{E0}(s) = \begin{bmatrix} G_{E0,RR}(s) & G_{E0,GR}(s) & G_{E0,BR}(s) \\ G_{E0,RG}(s) & G_{E0,GG}(s) & G_{E0,BG}(s) \\ G_{E0,RB}(s) & G_{E0,GB}(s) & G_{E0,BB}(s) \end{bmatrix}$$

$$= \begin{bmatrix} \frac{14.907 \cdot (s + 0.00799)}{s + 0.00083} & -\frac{0.582 \cdot (s + 0.00368)}{s + 0.00087} & \\ \frac{0.083 \cdot (s + 0.00229)}{s + 0.00083} & \frac{66.937 \cdot (s + 0.00864)}{s + 0.00087} & \\ \frac{0.014 \cdot (s + 0.00212)}{s + 0.00082} & -\frac{0.065 \cdot (s + 0.00167)}{s + 0.00083} & \\ -\frac{0.321 \cdot (s + 0.00346)}{s + 0.00085} & & \\ -\frac{0.125 \cdot (s + 0.00245)}{s + 0.00084} & & \\ 10.138 \cdot (s + 0.00847) & & \\ s + 0.00085 & & \end{bmatrix} \quad (50)$$

In this study, the decentralized control approach was applied to simplification, that is, relative gain array (RGA) method [31], [32] was introduced to measure of the interactions and diagonal dominance. The RGA of the plant G_{ES} is equal to identity matrix in the typical operating range $\omega = 10^{-4}$ to 10^3 rad/s as follows:

$$\Lambda(G_{ES}) = G_{ES} \cdot *(G_{ES}^T)^{-1}$$

$$= \begin{bmatrix} 1.00 + 0.00i & 0.00 + 0.00i & 0.00 + 0.00i \\ 0.00 + 0.00i & 1.00 + 0.00i & 0.00 + 0.00i \\ 0.00 + 0.00i & 0.00 + 0.00i & 1.00 + 0.00i \end{bmatrix} \equiv I \quad \forall \omega \quad (51)$$

where the operator “ $\cdot *$ ” denotes Schur (element by element) matrix multiplication. According to the rule of pairing selection, the plant G_{ES} is close to diagonal and essentially a collection of three independent subsystems. Therefore, the FFB loop is proper to treat as three single-input–single-output (SISO) loops, and the controller K is designed in diagonal form in proportional–integral (PI) strategy as follows:

$$K(s) = \begin{bmatrix} K_R(s) & 0 & 0 \\ 0 & K_G(s) & 0 \\ 0 & 0 & K_B(s) \end{bmatrix}$$

$$= \begin{bmatrix} K_{PR} + K_{IR}/s & 0 & 0 \\ 0 & K_{PG} + K_{IG}/s & 0 \\ 0 & 0 & K_{PB} + K_{IB}/s \end{bmatrix}. \quad (52)$$

According to the stability theorem [31], suppose that the plant G is stable, if RGA $\Lambda(G) = I \quad \forall \omega$, the stability of each of individual loops implies stability of the entire system. Therefore, the stability of the FFB loop is determined by the stability of the diagonal loops of three color LEDs independently. By using the Routh–Hurwitz stability test, the stabilities of three loops were evaluated, respectively. The stability conditions were $K_{PR} >$

Fig. 13. Simulation results of decoupled red LED loop. (a) Time responses of proportional control test. (b) Frequency responses of sensitivity function S_{ER} for PI control test.

-1.75 and $K_{IR} > 0$ for red, $K_{PG} > -0.66$ and $K_{IG} > 0$ for green, and $K_{PB} > -0.89$ and $K_{IB} > 0$ for blue LED loops.

The performance of PI controller is tuned by using SIMULINK in MATLAB. In this study, the control system requirements are defined as follows:

- 1) rise time (time for step response from 10% to 90%) < 1 s;
- 2) settling time (time to reach 98% of reference) < 4 s.

Using the time-domain simulation, optimal tuning may be carried out by finding the minimum of the integral of the absolute value of the error (IAE), which also satisfies the aforementioned system requirements, as follows:

$$IAE_i = \int_0^\infty |e_i(t)| dt, \quad \text{where } i = R, G, B \quad (53)$$

where the error is $e = [e_R \quad e_G \quad e_B]^T = \tilde{L}_c - \tilde{L}_s$.

The tuning procedures are simulated by step test. In the example of the decouple red LED loop [see Fig. 12(b)], the integral gain K_{IR} is first set at zero in order to find the effective range of proportional gain K_{PR} . The simulated responses of P control are not significant since the $K_{PR} > 11.0$, as shown in Fig. 13 (a). Second, the $K_{PR} = 7.0$ – 11.0 chosen for finding the minimum integral gain K_{IR} satisfied the requirements of rising time and settling time. Its simulated results of IAE are listed in

TABLE II
SIMULATION RESULTS OF PI CONTROL TEST OF DECOUPLED FEEDBACK LOOPS

Red LEDs			Green LEDs			Blue LEDs		
K_{PR}	K_{IR}	IAE_R	K_{PG}	K_{IG}	IAE_G	K_{PB}	K_{IB}	IAE_B
7	4.7	11.040	5	2.5	9.234	3	2.3	12.225
8	5.0	10.376	6	2.7	8.535	4	2.6	10.783
9	5.2	9.976	7	2.8	8.214	5	2.8	9.986
10	5.4	9.606	8	2.9	7.919	6	3.0	9.302
11	5.6	9.262	9	3.0	7.646	7	3.0	8.708

Fig. 14. Implementation of RGB LED lighting control system.

Table II. Third, the controller should be robust with respect to the plant uncertainty. A sensitivity function S_{ER} is defined for the closed-loop transfer function H_{ER} with respect to the variation of open-loop transfer function G_{ESR} as

$$S_{ER}(s) = \frac{\partial H_{ER}(s)}{\partial G_{ESR}(s)} \cdot \frac{G_{ESR}(s)}{H_{ER}(s)} = \frac{1}{1 + K_R(s) \cdot G_{ESR}(s)}. \quad (54)$$

The frequency responses of the S_{ER} are plotted in the controller parameters of Table II, as shown in Fig. 13(b). Consequently, the acceptable PI controller, satisfying the system requirements, the stability condition, the criterion of minimum IAE_R , and low sensitivity of the uncertainty of the plant G_{ESR} , is designed as $K_{PR} = 11.0$, $K_{IR} = 5.6$. Repeating the same procedures, the controller K is finally designed as follows:

$$K(s) = \begin{bmatrix} 11 + 5.6/s & 0 & 0 \\ 0 & 9 + 3.0/s & 0 \\ 0 & 0 & 7 + 3.0/s \end{bmatrix}. \quad (55)$$

V. EXPERIMENTAL RESULT AND DISCUSSION

A control system and a verification system, same as given in [15, Fig. 14 (b) and (c)], were set up for verification. For the control system, the designed converter N , compensator M , and controller K were implemented by using a PC with LabVIEW and a data acquisition card (DAQ), as shown in Fig. 14. Because of the limitation of the DAQ, the sampling time of discrete control was set $T = 0.1$ s. The discrete PI controller K' designed

with zero-order hold was obtained as follows:

$$K'(z) = \frac{1}{z-1} \begin{bmatrix} 11z + 10.44 & 0 & 0 \\ 0 & 9z + 8.7 & 0 \\ 0 & 0 & 7z + 6.7 \end{bmatrix}. \quad (56)$$

For the verification system, the sampling time of data logging for total luminous intensity was $T = 1.0$ s due to the limitation of the General Purpose Interface Bus (GPIB) card.

Two experiments were designed to verify the system performances in total luminous intensity output Φ_{OUT} and color difference of chromatic coordinate $\Delta u'v' = \sqrt{(u'_{OUT} - u'_0)^2 + (v'_{OUT} - v'_0)^2}$, where u'_0 and v'_0 are the initial desired chromaticity coordinates. In the transient experiments, the CCTs were set at constant 3800, 5000, and 6000 K, respectively; and the total luminous intensity commands Φ_r were applied sequentially from 2000 to 3500 cd in intervals of 500 cd with 120 s for each step. The CCT conditions of 3800 and 5000 K differ from identification conditions 3500 and 6000 K in order to verify the control capability for various input commands. The experimental results are listed in Table III. Both rise time and settling time of Φ_{OUT} are all within the requirements; the root-mean-square error (RMSE) of Φ_{OUT} and their signal-to-noise (SN) ratios show low steady-state error; and average $\Delta u'v'$ are shown low color drift as well. In the example of CCT 3800 K, the experimental responses are revealed in Fig. 15. First, the Φ_{OUT} follow the Φ_r and the $T_{CC,OUT}$ follow the $T_{CC,r}$, as shown in Fig. 15(a) and (b), respectively. Second, the color differences show effective regulation, as depicted in Fig. 15(b). Its responses at several step perturbation moments reveal large fluctuations; in that, the external electromagnetic disturbances, e.g., the power supply of driver, might interfere with the spectrometer; it is evident that there are no corresponding fluctuations to the Φ_{OUT} , T_{LED} , and L_S . Third, the junction temperature T_{LED} and heatsink temperature T_b revealed self-heating of LEDs, as shown in Fig. 15(c). Finally, measured radiant power L_S and electrical power P_{LED} of RGB LEDs are depicted in Fig. 15(d) and (e), respectively.

In the steady-state experiments, the input commands were set Φ_r at constant 3000 cd and CCT at 3800, 6000, and 8000 K, in turn, for the proposed control system. Moreover, the open-loop system driving constant electrical powers that are of the corresponding input commands at the initial time were tested as well. In addition, an extra 15 W thermal disturbance almost twice that of the power consumption of the RGB LED luminaire was applied during 4000–10 000 s for both the systems. It caused an approximate 30 °C junction temperature rise for each LEDs. The experimental results obtained during $t = 9000$ –10 000 s are listed in Table IV. For the proposed control system, the RMSE of Φ_{OUT} and average color difference $\Delta u'v'$ are both shown low steady-state error and low color drift, respectively. In the example of CCT 6000 K, the experimental responses are shown in Fig. 16. All the Φ_{OUT} , $T_{CC,OUT}$, and $\Delta u'v'$ of the proposed control system are indicated well regulation, as shown in Fig. 16(a)–(c). Fig. 16(d) illustrates the temperature rise during the experiment. T_{LED} and T_b dramatically rose at 4000 s.

Fig. 15. Experimental responses to a serial total luminous intensity command and constant CCT 3800 K for proposed control system. (a) Total luminous intensity output. (b) Chromatic output. (c) Temperature. (d) Radiant power. (e) Electrical power.

Correspondingly, the P_{LED} showed noticeable compensation in Fig. 16(e).

These results show that the proposed control system, including the converter N , the compensator M , and the controller K , is effective; that is, our results indicate that both luminous and color outputs can achieve the requirements despite temperature rise and the system can operate at wide range color command. Regarding the results of Tables III and IV, the SN ratios of RMSE of ϕ_{OUT} could be treated as a steady-state error and all

less than 2%, where typically within 1%–0.1% for the transient experiment and 1.6%–0.16% for the steady-state experiment. Meanwhile, all of the $\Delta u'v'$ were typically within 0.0035. These findings also support the hypothesis that the proposed control system can provide a wide color range of input command. It is evident that the system can operate at CCTs different from the identification conditions in the transient and steady-state experiments. Moreover, the RMSE of ϕ_{OUT} , as well as $\Delta u'v'$, showed slight variation and inconsistency among the CCT or

Fig. 16. Experimental responses to constant input command of $\Phi_r = 3000$ cd and $T_{CC,r} = 6000$ K for open-loop and the proposed control system. (a) Total luminous intensity output. (b) CCT output. (c) Color difference output. (d) Temperature of proposed control system. (e) Electrical power of proposed control system.

electrical power conditions. For the transient experiment, the discordant results should be mainly caused by lack of performance of K and accuracy of N ; besides, it further introduces the lack of accuracy of M for steady-state experiment due to large junction temperature rise. Therefore, the system performance could be further improved by obtaining precise N and M and

more accurate controller design, e.g., Robust Control [15]. The accuracy of N and M can be improved by providing more experimental data of system identification for the four submodels, i.e., E_P , E_T , Y_P , and Y_T .

For the steady-state experiment, the $\Delta u'v'$ results showed 0.00297 (maximum) and 0.00171 (minimum) by approximate

TABLE III
EXPERIMENTAL RESULTS OF THE TRANSIENT EXPERIMENTS

	Correlated Color Temperature		
	3,800K	5,000K	6,000K
Total luminous intensity Φ_{OUT}			
rise time T_r (s)			
2000cd $\rightarrow$ 2500cd	1.0	1.0	1.0
2500cd $\rightarrow$ 3000cd	1.0	1.0	1.0
3000cd $\rightarrow$ 3500cd	1.0	1.0	1.0
3500cd $\rightarrow$ 3000cd	1.0	1.0	1.0
3000cd $\rightarrow$ 2500cd	1.0	1.0	1.0
2500cd $\rightarrow$ 2000cd	1.0	1.0	1.0
settling time T_s (s)			
2000cd $\rightarrow$ 2500cd	3.0	3.0	3.0
2500cd $\rightarrow$ 3000cd	3.0	3.0	3.0
3000cd $\rightarrow$ 3500cd	3.0	3.0	3.0
3500cd $\rightarrow$ 3000cd	3.0	1.0	4.0
3000cd $\rightarrow$ 2500cd	4.0	1.0	4.0
2500cd $\rightarrow$ 2000cd	4.0	3.0	3.0
RMSE (cd)			
2000cd (60s-120s, 780s-840s)	3.50	20.68	8.31
2500cd (180s-240s, 660s-720s)	3.07	22.27	14.68
3000cd (300s-360s, 540s-600s)	3.39	20.69	21.70
3500cd (420s-480s)	3.94	20.02	27.96
SN ratio of RMSE (%)			
2000cd (60s-120s, 780s-840s)	0.18	1.03	0.42
2500cd (180s-240s, 660s-720s)	0.12	0.89	0.59
3000cd (300s-360s, 540s-600s)	0.11	0.69	0.72
3500cd (420s-480s)	0.11	0.57	0.80
Average color difference, $\Delta u'v'$ (-)			
2000cd (60s-120s, 780s-840s)	0.00313	0.00345	0.00225
2500cd (180s-240s, 660s-720s)	0.00269	0.00225	0.00142
3000cd (300s-360s, 540s-600s)	0.00287	0.00337	0.00295
3500cd (420s-480s)	0.00172	0.00340	0.00351

TABLE IV
EXPERIMENTAL RESULTS OF THE STEADY-STATE EXPERIMENTS

	Correlated Color Temperature		
	3,800K	6,000K	8,000K
Total luminous intensity output Φ_{OUT}			
RMSE (cd)			
proposed control system	47.91	27.23	4.75
open-loop system	281.99	259.60	256.20
SN ratio of RMSE (%)			
proposed control system	1.60	0.91	0.16
open-loop system	9.40	8.65	8.54
Average color difference $\Delta u'v'$ (-)			
proposed control system	0.00297	0.00207	0.00171
open-loop system	0.01292	0.01293	0.01268

color point changes in CIE 1960 are $\Delta uv = 0.004$ (FFB&TFF), 0.006 (CCFB), and 0.008 (CCFB) for a heatsink temperature change of 50 °C. Hoelen *et al.* [5], [7] demonstrated a maximum color point error $\Delta u'v'$ in white of 0.007 (FFB&TFF) with 35 °C and 0.0092 (FFB&TFF) and 0.0084 (CCFB) with 75 °C heatsink temperature change, respectively. Deurenberg *et al.* [6] pointed out that the temperature induced color accuracy errors of average $\Delta u'v' = 0.0035$ and 0.0048, respectively, for the FFB&TFF and CCFB systems for a heatsink temperature variation of 50 °C. Wang *et al.* [15] showed a typical $\Delta u'v' = 0.001$ under 25 °C junction temperature rise.

The proposed control system was discussed in-depth as follows. It appears that both N and M of the TFF loop provide accurate radiant command L_C to the following FFB loop. The FFB loop implemented in three SISO loops regulates the luminous intensity of RGB LEDs Φ_{LED} as well as the total luminous intensity output Φ_{OUT} . Moreover, the TFF loop compensates temperature variation further to regulate the color difference $\Delta u'v'$ and CCT output $T_{CC,OUT}$. A thermal–electrical–luminous–chromatic model, including five submodels, is derived from RGB LED luminaire, where the four submodels, i.e., E_P , E_T , Y_P , and Y_T , were modeled as temperature-dependent or electrical-dependent due to low quantum efficiency, spectral shift, and current droop by the junction temperature rise. Compared to [15], a converter and a compensator, which are designed as compact linear models and instead of a lookup table, are introduced in the TFF&FFB structure. The advantage is that the lighting system can operate at wide color range and would not restrict at specific CCT conditions. In contrast, the disadvantage is that the compensator must be remodeled by the four compact linear models in each control period due to the temperature-dependent and electrical-dependent properties. A diagonal PI

40 °C junction temperature variation. Earlier publications showed several comparable results for RGB LEDs as follows. Muthu *et al.* [4], [8] and Muthu and Gaines [9] reported that the

controller designed by decentralized control approach is shown concise and effective. The diagonal effect is because the photon emission is dominated by the electrical power of the corresponding color LEDs, and the thermal interaction is minor in contrast to the optical effect.

VI. CONCLUSION

This paper has proposed a novel FFB&TFF structure for an RGB LED lighting control system, in which a converter was applied for command conversion and a compensator was used to compensate the temperature variation and to adjust the signal mismatch between the converter outputs and initial responses of RGB LEDs. The RGB LED luminaire was modeled and experimentally identified as a thermal–electrical–luminous–chromatic model, including five submodels, where T-L, T-C, and E-C models were treated as functions of electrical power and E-L model as a function of junction temperature in order to simplify the modeling calculation of the compensator. The converter was obtained from the experimental results of T-C model identification. From the point of view of decentralized control approach, the control system designed in the three SISO loops with PI diagonal controller could guarantee system stability and performance. Finally, the designed controller was implemented for experimental verification. The experimental results of both transient and steady-state experiments showed low color drift and low total luminous intensity droop. Compared to previous work [15], the novel FFB&TFF control structure can operate at a wide color range and would not restrict at specific CCT conditions. The proposed control system were shown to be effective.

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