Multivariable Robust Control for a Red–Green–Blue LED Lighting System

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Abstract—This paper proposes a novel control structure for a red–green–blue (RGB) LED lighting system, and applies multivariable robust control techniques to regulate the color and luminous intensity outputs. RGB LED is the next-generational illuminant for general lighting or liquid crystal display backlighting. The most important feature for a polychromatic illuminant is color adjustability; however, for lighting applications using RGB LEDs, color is sensitive to temperature variations. Therefore, suitable control techniques are required to stabilize both luminous intensity and chromaticity coordinates. In this paper, a robust control system was proposed for achieving luminous intensity and color consistency for RGB LED lighting in a three-step process. First, a multivariable electrical–thermal model was used to obtain RGB LED luminous intensity, in which a lookup table served as a feedforward compensator for temperature and power variations. Second, robust control algorithms were applied for feedback control design. Finally, the designed robust controllers were implemented to control the luminous and chromatic outputs of the system. From the experimental results, the proposed multivariable robust control was damned effective in providing steady luminous intensity and color for RGB LED lighting.

Index Terms—Color difference, luminous intensity, red–green–blue (RGB) LEDs, robust control, thermal–electrical–luminous model.

I. INTRODUCTION

RECENTLY, LED has been drawing much attention as a state-of-the-art illuminator because of its numerous advantages, including energy savings, long lifetime, and environmental friendliness. Red–green–blue (RGB) LEDs can provide a wide color gamut for liquid crystal display (LCD) backlighting, as well as full color adjustability for general lighting applications [1], [2]. This newly developed illuminant is the only light source currently capable of this type of vivid and dynamic lighting performance. However, the tunable light outputs have been found to induce light consistency issues for RGB LED lighting, because the luminous intensity and color outputs are easily influenced by junction temperature variations caused by self-heating of the LEDs and disturbances in ambient temperatures. Therefore, proper control strategies are required to stabilize light output in order to counteract temperature variations.

To control RGB LED lighting systems, the selection of feedback signals is an important issue. Muthu *et al.* [3]–[5] applied three kinds of feedback system: color coordinate feedback with temperature feedforward (CCFB and TFF), color coordinate feedback (CCFB), and flux feedback with temperature feedforward (FFB and TFF). The color coordinates were measured by photodiodes with color filters and the fluxes with photodiodes with a time-division method. In addition, the heat sink temperature and thermal resistance were used to estimate junction temperature for temperature feedforward compensation. Hoelen *et al.* [6]–[8] further discussed light outputs and applied four control structures, namely, flux feedback, temperature feedforward, CCFB, and FFB and TFF. Among these, CCFB and FFB and TFF were shown to provide better color consistency for RGB LED lighting than did the others, when the system was experiencing junction temperature variations. Until now, CCFB has been a popular choice for application to control system design [9]–[13] because of its simple structure. However, the accuracy of feedback signals is limited by the difference between the spectra of filtered sensor and color matching functions. In contrast, the FFB and TFF structure can provide more signals for control design, but requires double loops and information about the junction temperature. For controller design, traditional control methodologies such as proportional–integral (PI) or PI derivative (PID) based algorithms have been applied to control RGB LED lighting systems [5], [7], [14], [15]. However, these methods cannot guarantee the stability and performance of systems with perturbations such as varying input power or junction temperatures. Therefore, advanced control strategies should be considered for improving system performance. In this paper, a novel control structure is proposed, and robust control techniques are applied, to achieve consistent luminous intensity and color. The effect will be experimentally verified.

The paper is arranged as follows. In Section II, an RGB LED luminaire is modeled as a multivariable system and a feedback control structure is proposed. In Section III, robust control strategies are introduced for multivariable controller design. Then, the designed controller is implemented for performance analysis in Section IV. Finally, some conclusions are drawn in Section V.

II. SYSTEM DESCRIPTION AND MODELING

A. System Description

To regulate the color and luminous intensity of RGB LED lighting, a novel control structure is proposed, as shown in Fig. 1. In this structure, T_{CCR} and Φ_r , respectively, represent the correlated color temperature (CCT) and total luminous intensity commands, while Φ is the luminous intensity output. Using

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Fig. 1. Control structure of the RGB LED lighting system (solid lines: scalar signals; mesh lines: 3×1 vector signals).

Fig. 2. Illustration of multiphysical phenomenon for RGB LED luminaire.

a lookup table M , the commands are converted to the corresponding radiant power signal $L_C = [L_{CR} \ L_{CG} \ L_{CB}]^T$, in which the subscripts “R,” “G,” and “B,” respectively, represent the “red,” “green,” and “blue” components of the signal. The controller K is used to calculate a suitable electrical power $P_E = [P_R \ P_G \ P_B]^T$ according to the error signal e . Furthermore, the dynamics of the RGB LED luminaire are modeled as G_E , with the output of luminous intensity $\Phi_{LED} = [\Phi_R \ \Phi_G \ \Phi_B]^T$. The summation matrix U is defined as $U = [1 \ 1 \ 1]_{1 \times 3}$ such that the total luminous intensity Φ is the combination of individual luminous intensity, i.e., $\Phi = U\Phi_{LED} = \Phi_R + \Phi_G + \Phi_B$.

The RGB LED luminaire is a lighting fixture composed of multiple RGB LED lamps. The RGB color LEDs can be operated by three individual electrical power sources to emit photons for lighting and simultaneously generate heat to raise junction temperature. Then the photons can stimulate retinas to produce luminous and chromatic perception, as illustrated in Fig. 2.

The electrical power P_E can be normalized as $0 \leq P_E \leq 1$, compared to the maximum power, and further divided into the following two terms:

$$P_E = P_T + P_O \quad (1)$$

Fig. 3. Electrical—thermal—luminous model.

where P_T is the normalized thermal power for heat generation and P_O is the normalized optical power for lighting. Therefore, P_T and P_O can be represented as

$$P_T = (I - \alpha) P_E \quad (2)$$

$$P_O = \alpha P_E \quad (3)$$

where α is the diagonal power factor matrix, which represents the quantum efficiency of the LEDs.

Therefore, the LED luminaire model G_E can be described as a combination of three submodels, namely, the electrical–thermal ($E-T$) model H , the electrical–luminous ($E-L$) model E_P , and the thermal–luminous ($T-L$) model E_T , as illustrated in Fig. 3, in which the luminous intensity Φ_{LED} is expressed as

$$\Phi_{LED} = \Phi_P + \Phi_T = E_P P_E + E_T T_j = (E_P + E_T H) P_E \quad (4)$$

where $T_j = [T_R \ T_G \ T_B]^T$ is the junction temperature, i.e., the dynamic model of G_E can be represented as

$$G_E = \frac{\Phi_{LED}}{P_E} = E_P + E_T H. \quad (5)$$

The three submodels of the RGB LED luminaire can be derived by the input–output relation. First, the $E-T$ model H represents the influence of junction temperature by the thermal power P_T as in the following relation:

$$\Delta T_j = H P_E = \begin{bmatrix} H_{RR} & H_{GR} & H_{BR} \\ H_{RG} & H_{GG} & H_{BG} \\ H_{RB} & H_{GB} & H_{BB} \end{bmatrix} \begin{bmatrix} P_R \\ P_G \\ P_B \end{bmatrix} \quad (6)$$

where ΔT_j represents the variation of junction temperature. Second, the $T-L$ model E_T represents the luminous intensity variation by the junction temperature as follows:

$$\Phi_T = E_T \Delta T_j = \begin{bmatrix} E_{TR} & 0 & 0 \\ 0 & E_{TG} & 0 \\ 0 & 0 & E_{TB} \end{bmatrix} \begin{bmatrix} \Delta T_R \\ \Delta T_G \\ \Delta T_B \end{bmatrix}. \quad (7)$$

Third, the $E-L$ model E_P represents the luminous intensity variation by optical power P_O as in the following:

$$\Phi_P = E_P P_E = \begin{bmatrix} E_{PR} & 0 & 0 \\ 0 & E_{PG} & 0 \\ 0 & 0 & E_{PB} \end{bmatrix} \begin{bmatrix} P_R \\ P_G \\ P_B \end{bmatrix}. \quad (8)$$

Fig. 4. Illustration of RGB LED driving circuits.

B. System Identification of RGB LED Luminaire

The RGB LED luminaire system was used for system identification. As illustrated in Fig. 4, five RGB LED lamps [16] were installed on a 900-g aluminum heat sink (see Fig. 2) to allow the junction temperature variation by self-heating to be kept small through good thermal design. Four lamps were packaged in the front side for lighting, while the fifth was combined with a silicon photodiode [17] and assembled inside the luminaire to measure the junction temperature and radiant power (i.e., the fifth LED was used as sensors) [18]. In addition, each LED was driven by a 350 mA constant dc pulsewidth modulation (PWM), whose switching frequency was set at 120 Hz to avoid flick perception [18], [19]. According to the duty cycle commands, the normalized irreducible tensorial matrix (NITM) data acquisition (DAQ) system generated corresponding transistor–transistor logic (TTL) PWM signals, which were then connected to MOSFETs to drive the LEDs. Three independent circuits were used for power operation and measurement of the RGB LEDs through the DAQ system. The electrical power P_E could be decided by the duty cycles of the PWM signals.

The junction temperature could be estimated by the inside LED lamp using the pulse forward voltage method [20]–[23]. At first, given a 1 mA constant current input for 50 μ s, the temperature-sensitive parameter S_T is obtained from the experiments by comparing the junction temperature and the voltage output as follows:

$$S_T = \begin{bmatrix} S_{TR} & 0 & 0 \\ 0 & S_{TG} & 0 \\ 0 & 0 & S_{TB} \end{bmatrix} = \begin{bmatrix} 1.82 & 0 & 0 \\ 0 & 5.90 & 0 \\ 0 & 0 & 2.20 \end{bmatrix} \times 10^{-3}. \quad (9)$$

Therefore, the junction temperature T_j can be estimated by measuring the average forward voltage $V_{LOW} = [V_R \ V_G \ V_B]^T$ at the OFF interval of dc PWM by using 1 mA constant current, as in the following:

$$T_j = S_T V_{LOW}. \quad (10)$$

Meanwhile, the radiant powers of RGB LEDs can be measured by the silicon photodiode using the time-division method, in which the sensed radiant power $L_S = [L_R \ L_G \ L_B]^T$ is calculated by the photodiode response, given time-shift PWM

TABLE I
EXPERIMENTAL RESULTS OF PHOTODIODE MODEL

Exp.	Power (%)			Exp.	Power (%)			Exp.	Power (%)		
	P_G	P_B	S_{DR}		P_R	P_B	S_{DG}		P_R	P_G	S_{DB}
R1	20	14	0.0291	G1	60	14	0.0213	B1	60	20	0.1085
R2	25	21	0.0285	G1	70	21	0.0212	B2	70	25	0.1079
R3	30	28	0.0285	G1	80	28	0.0211	B3	80	30	0.1069
Average: 0.0287				Average: 0.0212				Average: 0.1077

Fig. 5. Experiment responses of Φ versus L_R .

Fig. 6. Apparatus for measurement and data logging of total luminous intensity, correlative color temperature, and chromaticity coordinate in CIE 1976 UCS.

signals, as [4]

$$L_S = S_D \Phi_{LED} = \begin{bmatrix} S_{DR} & 0 & 0 \\ 0 & S_{DG} & 0 \\ 0 & 0 & S_{DB} \end{bmatrix} \Phi_{LED} \quad (11)$$

in which the photodiode model S_D was obtained from the experiments, as illustrated in Table I. For example, in experiment R1, the electrical power for the green and blue LEDs was fixed at $P_G = 20\%$ and $P_B = 14\%$. Then, the electrical power for the red LED was changed from $P_R = 50\%$ to $P_R = 90\%$. The corresponding luminous intensity Φ and the sensed radiant power L_R were measured, as shown in Fig. 5, to model $L_R = S_{DR} \Phi_R = 0.0291 \Phi_R$ using the linear regressive method. Note that the variation of Φ equals the variation of Φ_R since

Fig. 7. Experimental response of electrical-thermal model H_{RR} . (a) Time-domain responses. (b) Frequency-domain responses.

176 $\Phi = \Phi_R + \Phi_G + \Phi_B$. In Table I, S_{DR} from the three experi-
 177 ments (R1, R2, and R3) are similar, such that an average value
 178 $S_{DR} = 0.0287$ was selected to represent the model. Similarly,
 179 S_{DG} and S_{DB} were experimentally obtained as follows:

$$S_D = \begin{bmatrix} S_{DR} & 0 & 0 \\ 0 & S_{DG} & 0 \\ 0 & 0 & S_{DB} \end{bmatrix} = \begin{bmatrix} 0.0287 & 0 & 0 \\ 0 & 0.0212 & 0 \\ 0 & 0 & 0.1077 \end{bmatrix}. \quad (12)$$

180 A set of instruments was built to measure the luminous and
 181 chromatic outputs of the system. As illustrated in Fig. 6, the
 182 polychromatic light output was projected into an integrating
 183 sphere for color mixing, such that the total luminous intensity Φ
 184 could be measured by the photopic detector. In addition, the light
 185 spectrum was acquired by a spectrometer to allow calculation of
 186 CCT T_{CC} and chromaticity coordinate W in Cleveland Institute
 187 of Electronics (CIE) 1976 uniform chromaticity scale (UCS)
 188 [19]. A personal computer was used for process control and
 189 data logging.

191 The dynamics of the RGB LED luminaire G_E can be ob-
 192 tained by the identification of the three submodels in (6)–(8).
 193 First, for the E - T model H , the experiments were carried
 194 out as in the following. At first, the maximum power was
 195 set as $P_{E,max} = [1.21 \ 2.56 \ 1.27]^T$ W for a single RGB
 196 LED lamp, and the normalized operation power was set as
 197 $P_E = [30 \ 30 \ 30]^T$ %. Then, step perturbations of P_R , P_G ,
 198 and P_B were applied, in turn, as system inputs, and the corre-
 199 sponding junction temperature variations were measured as sys-
 200 tem outputs. For example, Fig. 7(a) illustrates the system output
 201 of the experiment R1 (with a step input P_R from 30% to 65%).
 202 Therefore, H_{RR} can be obtained by the Rake's method [24] as
 203 follows:

$$H_{RR}(s) = \frac{0.0659(s + 0.00153)}{(s + 0.00083)}.$$

204 The experimental time-domain data were transferred to fre-
 205 quency domain by the fast Fourier transform (FFT) and com-
 206 pared with the bode plot of $H_{RR}(s)$, as illustrated in Fig. 7(b).
 207

From the comparison of time-domain and frequency-domain
 responses in Fig. 7, the first-order model is sufficient to capture
 the basic system dynamics, as discussed in [25]. The results of
 system identification at different operating points are illustrated
 in Table II.

The T - L model E_T represents the transmission path from
 junction temperature to luminous intensity, which can be de-
 scribed as a constant gain due to the short lifetime of pho-
 tons [26], [27]. The identification was conducted at different
 operating points, as illustrated in Table III, where the heat sink
 was heated by a thermal pad. The identification results obtained
 by measuring the junction temperature and the corresponding
 luminous intensity are shown in Table III. Fig. 8 illustrates the
 variation of E_{TR} at the three operating conditions.

Similarly, the E - L model E_P represents the transmission
 path from electrical power P_E to luminous intensity, which can
 also be considered a constant gain [26], [27]. The experiments
 were the same as the previous identification of E_T , but with
 the electrical power P_E and luminous intensity as system inputs
 and outputs, respectively. The operating points and identification
 results are illustrated in Table IV. Fig. 9 illustrates the variations
 of E_{PR} at the six operating conditions.

C. Feedforward Compensator

The feedforward compensator M is a lookup table for con-
 verting the CCT T_{CCr} and total luminous intensity Φ_r inputs
 into the corresponding radiant power L_C at different junction
 temperature T_j and nominal input power P_E in order to main-
 tain consistent light output. Therefore, the multidimensional
 function M can be described as

$$L_C = M(T_{CCr}, \Phi_r, T_j, P_E) \quad (13)$$

such that the radiant power vector L_C is determined by the
 inputs T_{CCr} and Φ_r , and the operating conditions T_j and P_E .
 In experiments, the values of M are measured at many operat-
 ing points, and finally, decided upon by using the interpolation
 method. For example, Table V illustrates the relations of L_C to
 T_{CCr} and Φ_r [18].

TABLE II
IDENTIFICATION RESULTS OF THE ELECTRICAL-THERMAL MODEL H

Step P_R (%)	NO.	H_{RR}			NO.	H_{RG}			NO.	H_{RB}		
		pole	zero	gain		pole	zero	gain		pole	zero	gain
30→65	1	-0.00083	-0.00153	0.0659	5	-0.00083	-0.00229	0.0268	9	-0.00082	-0.00212	0.0264
65→100	2	-0.00080	-0.00227	0.0318	6	-0.00074	-0.00236	0.0259	10	-0.00073	-0.00221	0.0247
100→65	3	-0.00088	-0.00231	0.0320	7	-0.00081	-0.00181	0.0326	11	-0.00084	-0.00189	0.0293
65→30	4	-0.00083	-0.00156	0.0671	8	-0.00083	-0.00224	0.0283	12	-0.00084	-0.00222	0.0260

Step P_G (%)	NO.	H_{GR}			NO.	H_{GG}			NO.	H_{GB}		
		pole	zero	gain		pole	zero	gain		pole	zero	gain
30→65	13	-0.00087	-0.00368	0.0577	17	-0.00087	-0.00157	0.1853	21	-0.00083	-0.00167	0.1204
65→100	14	-0.00085	-0.00342	0.0562	18	-0.00084	-0.00124	0.2834	22	-0.00085	-0.00171	0.1104
100→65	15	-0.00085	-0.00316	0.0603	19	-0.00085	-0.00126	0.2794	23	-0.00086	-0.00179	0.1075
65→30	16	-0.00073	-0.00347	0.0549	20	-0.00073	-0.00141	0.1819	24	-0.00075	-0.00185	0.1051

Step P_B (%)	NO.	H_{BR}			NO.	H_{BG}			NO.	H_{BB}		
		pole	zero	gain		pole	zero	gain		pole	zero	gain
30→65	25	-0.00080	-0.00297	0.0372	29	-0.00082	-0.00256	0.0400	33	-0.00075	-0.00128	0.1095
65→100	26	-0.00083	-0.00245	0.0406	30	-0.00078	-0.00197	0.0447	34	-0.00080	-0.00112	0.1703
100→65	27	-0.00085	-0.00346	0.0318	31	-0.00084	-0.00245	0.0404	35	-0.00085	-0.00121	0.1691
65→30	28	-0.00079	-0.00317	0.0340	32	-0.00079	-0.00208	0.0458	36	-0.00081	-0.00129	0.1135

TABLE III
IDENTIFICATION RESULTS OF THE THERMAL-LUMINOUS MODEL E_T

P_R (%)	E_{TR} (cd / °C)	P_G (%)	E_{TG} (cd / °C)	P_B (%)	E_{TB} (cd / °C)
90.0	-12.88	35.0	-4.65	35.0	-0.68
70.0	-10.09	25.0	-3.09	21.0	-0.54
50.0	-7.32	15.0	-1.62	7.0	-0.33

III. ROBUST CONTROL DESIGN

From the previous identification results, the model variation was noted and should be considered for the controller design. Robust control is well known for its ability to cope with system variations and disturbances. Therefore, in this section, robust control strategies will be introduced. From the analyses of gap metrics and coprime factorization, a robust controller is designed that provides the maximum stability bound for the RGB LED lighting system. The resulting controller will then be implemented and experimentally verified in Section IV.

Fig. 8. Experimental response of the thermal-luminous model ETR.

Theorem 1 (Small Gain Theorem [28]): Suppose that $Z \in RH_\infty$ and let $\gamma > 0$. Then, the interconnected system shown in Fig. 10 is well posed and internally stable for all $\Delta(s) \in RH_\infty$ with: 1) $\|\Delta\|_\infty \leq 1/\gamma$ if and only if $\|Z(s)\|_\infty < \gamma$ and 2) $\|\Delta\|_\infty < 1/\gamma$ if and only if $\|Z(s)\|_\infty \leq \gamma$, where $\|Z\|_\infty$ is the ∞ norm of system Z .

TABLE IV
IDENTIFICATION OF ELECTRICAL-LUMINOUS MODEL E_P

T_R	E_{PR}	T_G	E_{PG}	T_B	E_{PB}
(°C)	(cd/(% P_R))	(°C)	(cd/(% P_G))	(°C)	(cd/(% P_B))
40	14.200	40	67.510	40	10.229
45	14.899	45	68.837	45	10.288
50	15.572	50	69.487	50	10.340
55	16.237	55	70.111	55	10.397
60	16.911	60	70.638	65	10.466
65	17.650	65	71.085	65	10.530

TABLE V
PARTIAL LOOKUP TABLE OF RADIANT POWER FOR RED LEDs

Radiant power of Red LEDs, L_R (a.u.)	Total luminous intensity Φ_r (cd)				
	2,000	2,500	3,000	3,500	4,000
4,000	29.462	36.841	44.221	51.600	58.979
CCT, 5,000	27.750	34.700	41.650	48.600	55.551
T_{CCr} , 6,000	26.017	32.533	39.050	45.566	52.082
(K) 7,000	24.264	30.342	36.419	42.496	48.574
8,000	22.491	28.124	33.738	39.391	45.024

260 Assume that a nominal plant G_0 can be expressed as $G_0 =$
 261 $\tilde{M}^{-1}\tilde{N}$, where: 1) $\tilde{M}, \tilde{N} \in RH_\infty$ and 2) $\tilde{M}\tilde{M}^* + \tilde{N}\tilde{N}^* = I\forall\omega$.
 262 This is called the *normalized left coprime factorization* of G_0 .
 263 In addition, suppose that a perturbed system G_Δ is represented
 264 as

$$G_\Delta = (\tilde{M} + \Delta_{\tilde{M}})^{-1} (\tilde{N} + \Delta_{\tilde{N}}) \quad (14)$$

265 with $\|[\Delta_{\tilde{M}} \ \Delta_{\tilde{N}}]\|_\infty < \varepsilon$ and $\Delta_{\tilde{M}}, \Delta_{\tilde{N}} \in RH_\infty$. Considering
 266 the control structure of Fig. 11, the system transfer function can
 267 rearranged as follows:

$$\begin{aligned} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} &= \begin{bmatrix} K \\ I \end{bmatrix} (I - G_0 K)^{-1} M^{-1} \\ \omega &= \begin{bmatrix} K \\ I \end{bmatrix} (I - G_0 K)^{-1} [I \ G_0] \omega \\ \omega &= [\Delta_{\tilde{M}} \ \Delta_{\tilde{N}}] \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}. \end{aligned} \quad (15)$$

268 Therefore, from Theorem 1, the closed-loop system remains
 269 internally stable for all $\|[\Delta_{\tilde{M}} \ \Delta_{\tilde{N}}]\|_\infty < \varepsilon$ if and only if
 270

$$\left\| \begin{bmatrix} K \\ I \end{bmatrix} (I - G_0 K)^{-1} [I \ G_0] \right\|_\infty \leq \frac{1}{\varepsilon}. \quad (16)$$

271 Furthermore, the stability margin of the system can be defined
 272 as follows.

Fig. 9. Experimental response of the electrical-luminous model E_{PR} .

Fig. 10. Illustration of small gain theorem.

Fig. 11. Block diagram of the perturbed plant G_Δ with controller K .

273 **Definition 1 (Stability Margin [29]):** The stability margin
 274 $b(G, K)$ of the closed-loop system is defined as

$$b(G, K) = \left\| \begin{bmatrix} K \\ I \end{bmatrix} (I - GK)^{-1} [I \ G] \right\|_\infty^{-1}. \quad (17)$$

275 Hence, from Theorem 1, the closed-loop system is internally
 276 stable for all $\|[\Delta_{\tilde{M}} \ \Delta_{\tilde{N}}]\|_\infty < \varepsilon$ if and only if $b(G, K) \geq \varepsilon$.
 277 However, the coprime factorization of a system may not be
 278 unique. Hence, the gap between two systems G_0 and G_Δ
 279 is defined as follows.

280 **Definition 2 (Gap Metric [28]):** The smallest value of
 281 $\|[\Delta_{\tilde{M}}, \Delta_{\tilde{N}}]\|_\infty$ that perturbs G_0 into G_Δ is called the gap between
 282 G_0 and G_Δ , and is denoted by $\delta(G_0, G_\Delta)$.

283 From the definitions, $b(G, K)$ gives the radius (in terms of
 284 gap metric) of the largest ball of plants stabilized by the controller K .
 285 Therefore, the goal of the controller design is to derive
 286 a suitable controller K from a nominal plant G_0 , such that all
 287 perturbed plants G_i located inside the gap $\delta(G_0, G_i) < \varepsilon$ will
 288 satisfy $b(G, K) \geq \varepsilon$ and the closed-loop system will remain
 289 internally stable, i.e., the variations (tolerances) of LEDs can
 290 be experimentally tested in the manufacturing processes, and

used to design suitable robust controllers that can guarantee the system stability.

A. Selection of the Nominal Plant

The selection of the nominal plant G_0 for the RGB LED luminaire was based on the system gaps between all transfer functions of G_E such that the maximum gap is minimized as

$$\min_{G_0} \max_{G_i} \delta(G_0, G_i) \quad (18)$$

where G_i represents all possible models of G_E . Considering (5), where $G_E = E_p + E_T H$ with the models of H , E_P , and E_T at all operating conditions, it can be derived that $\delta(G_0, G_i) \leq \delta(E_{P0}, E_{Pi}) + \delta(E_{T0}H_0, E_{Ti}H_i)$. Furthermore, it is noted that $\delta(E_{P0}, E_{Pi}) \leq 0.0075$ from Table III, and $\delta(E_{T0}H_0, E_{Ti}H_i) \leq 0.3748$ from Tables I and II, (*) shown at the bottom of this page.

Therefore, $\delta(G_0, G_i) \leq \delta(E_{P0}, E_{Pi}) + \delta(E_{T0}H_0, E_{Ti}H_i) = 0.3823$ with the following nominal plant $G_0 = E_{P0} + E_{T0}H_0$ for the RGB LED luminaire: shown (19) at the bottom of this page.

Note that the maximum gap can be regarded as the maximum system perturbation due to the variation of operating conditions, such as the input power P_E and the junction temperature T_j .

B. Controller Synthesis

The design procedures of the robust controller can be illustrated as follows [30]–[33].

1) *Loop-shaping design*: The nominal plant G_0 is shaped by precompensator W_1 and postcompensator W_2 to form a shaped plant $G_s = W_2 G W_1$, as shown in Fig. 12(a).

Fig. 12. Design procedures of robust controllers.

Fig. 13. Simplified RGB LED lighting control system for robust controller design.

2) *Robust stabilization estimate*: The maximum stability margin $b_{\max}$ is defined as

$$b_{\max}(G_s, K) \triangleq \inf_{K \text{ stabilizing}} \left\| \begin{bmatrix} K \\ I \end{bmatrix} (I - G_s K)^{-1} \begin{bmatrix} I & G_s \end{bmatrix} \right\|_{\infty}^{-1} \quad (20)$$

where M_s and N_s are the normalized left coprime factorization of G_s , i.e., $G_s = \tilde{M}_s^{-1} \tilde{N}_s$. If $b_{\max}(G_s, K) \ll 1$, then one must return to step (1) to modify W_1

$$H_0 = \begin{bmatrix} \frac{0.0659(s + 0.00153)}{(s + 0.00083)} & \frac{0.0577(s + 0.00368)}{(s + 0.00087)} & \frac{0.0318(s + 0.00346)}{(s + 0.00085)} \\ \frac{0.0268(s + 0.00229)}{(s + 0.00083)} & \frac{0.1853(s + 0.00157)}{(s + 0.00087)} & \frac{0.0404(s + 0.00245)}{(s + 0.00084)} \\ \frac{0.0264(s + 0.00212)}{(s + 0.00082)} & \frac{0.1204(s + 0.00167)}{(s + 0.00083)} & \frac{0.1691(s + 0.00121)}{(s + 0.00085)} \end{bmatrix}$$

$$E_{T0} = \begin{bmatrix} -10.09 & 0 & 0 \\ 0 & -3.09 & 0 \\ 0 & 0 & -0.54 \end{bmatrix} \quad E_{P0} = \begin{bmatrix} 15.572 & 0 & 0 \\ 0 & 67.510 & 0 \\ 0 & 0 & 10.229 \end{bmatrix}. \quad (*)$$

$$G_0(s) = \begin{bmatrix} \frac{14.9071(s + 0.00153)}{(s + 0.00083)} & \frac{-0.5822(s + 0.00368)}{(s + 0.00087)} & \frac{-0.3209(s + 0.00346)}{(s + 0.00085)} \\ \frac{-0.0828(s + 0.00229)}{(s + 0.00083)} & \frac{66.9374(s + 0.00157)}{(s + 0.00087)} & \frac{-0.1248(s + 0.00245)}{(s + 0.00084)} \\ \frac{-0.0143(s + 0.00212)}{(s + 0.00082)} & \frac{-0.0650(s + 0.00167)}{(s + 0.00083)} & \frac{10.1377(s + 0.00121)}{(s + 0.00085)} \end{bmatrix}. \quad (19)$$

Fig. 14. Implementation of RGB LED lighting control system. (a) Illustration of the control structure. (b) Layouts of the experimental instruments. (c) Experimental settings.

Fig. 15. Experimental responses to constant radiant power inputs with thermal disturbances. (a) Temperature variations. (b) Radiant power responses L_S . (c) Total luminous intensity Φ . (d) Color difference in CIE 1976 UCS $\Delta u'v'$.

and W_2 . Then, an $\varepsilon \leq b_{\max}(G_s, K)$ is selected to synthesize a stabilizing controller K_∞ , which satisfies $\left\| \begin{bmatrix} K_\infty \\ I \end{bmatrix} (I - G_s K_\infty)^{-1} \begin{bmatrix} I & G_s \end{bmatrix} \right\|_\infty^{-1} \geq \varepsilon$, as shown in Fig. 12(b).

3) Finally, the designed controller K_∞ is multiplied by the weighting functions, i.e., $K = W_1 K_\infty W_2$, and implemented to control system G , as illustrated in Fig. 12(c).

In Fig. 1, the compensator M converted the commands T_{CCR} and Φ_r into corresponding radiant power signal L_C . Therefore, the controller design can be simplified as Fig. 13, in which the nominal plant of the RGB LED luminaire is defined as $\bar{G}_0 = S_D G_0$. Using the aforementioned controller design techniques, the optimal H_∞ robust controller was designed as

$$K(s) = \begin{bmatrix} -0.4196 & 0.0098 & 0.0047 \\ 0.0146 & -1.4141 & 0.0047 \\ 0.0135 & 0.0122 & -1.0898 \end{bmatrix} \quad (21)$$

with a stability bound $b(\bar{G}_0, K) = 1$, which is much larger than the system gap. Therefore, the controller can stabilize the system even with plant perturbations. However, the steady state of L_S due to a unit step input $L_C = [1 \ 1 \ 1]^T$ can be calculated as

TABLE VI
STATISTICAL DATA FROM FIG. 15

RMS Error		Thermal disturbance (time duration for verification)			
		0W (250s-500s)	5W (750s-1000s)	10W (1250s-1500s)	15W (1750s-2000s)
Radiant power (a.u.)	Red LEDs, L_R	0.1806	0.1821	0.1878	0.1991
	Green LEDs, L_G	0.0496	0.0472	0.0480	0.0509
	Blue LEDs, L_B	0.0362	0.0356	0.0364	0.0369
Total luminous intensity Φ (cd)		2.641	4.094	5.151	5.532

follows:

$$\lim_{t \rightarrow \infty} L_S(t) = \lim_{s \rightarrow 0} s \bar{G}_0 K (I + \bar{G}_0 K)^{-1} \frac{1}{s} = [1.1072 \ 1.0075 \ 1.0696]^T$$

i.e., there is steady-state error due to a unit step input. Therefore, the following weighting function with integrals was used to

Fig. 16. System responses to a serial luminous intensity step input. (a) Total luminous intensity. (b) Color difference in CIE 1976 UCS. (c) Radiant power. (d) Temperature variation.

eliminate the steady-state error [34]:

$$W_1(s) = \frac{1}{s} \begin{bmatrix} \frac{1}{0.4196} & 0 & 0 \\ 0 & \frac{1}{1.4141} & 0 \\ 0 & 0 & \frac{1}{1.0898} \end{bmatrix}.$$

Using the loop-shaping techniques with $G_s = \bar{G}_0 W_1$, the robust controller was design as

$$K'(s) = W_1 K_\infty = \frac{1}{s} \begin{bmatrix} -2.3832 & 0.0042 & -0.0031 \\ -0.0012 & -0.7072 & -0.0020 \\ 0.0012 & 0.0026 & -0.9176 \end{bmatrix}$$

with a stability bound $b(\bar{G}_0, K') = 0.7071$, which was smaller than in the previous design (1), but still much larger than the maximal system gap (0.3823). However, the integral terms can guarantee zero steady-state error of the system due to step inputs, i.e., the use of W_1 sacrificed a little stability bound, but guaranteed zero steady-state errors to a step command. Therefore, the choice of weighting functions was a compromise between system performance and stability specifications. In the next section, the designed controller K' will be implemented for experimental verification.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental setup of the RGB LED lighting control system is illustrated in Fig. 14. Fig. 14(a) illustrates the control structure in which the measurement and control signals were transmitted through a DAQ system, NI PCI6229, to the PC-based controller. Fig. 14(b) shows the experimental layouts for the control loop (on the left) and data measurement (on the right) to verify the output luminous and chromatic properties. The overall experimental settings are illustrated in Fig. 14(c). For controller implementations, $K'(s)$ was first converted into discrete time as in the following:

$$K'(z) = \frac{1}{z-1} \begin{bmatrix} -0.2383 & 0.0004 & -0.0003 \\ -0.0001 & -0.0707 & -0.0002 \\ 0.0001 & 0.0003 & -0.0918 \end{bmatrix}$$

with a sampling time $T = 0.1$ s. During the experiments, the CCT T_{CC0} was set at 6000 K. Implemented with the controller K' , the system performance can be discussed by the rms error of the luminous intensity and the color difference of chromaticity coordinate outputs, which should be as small as possible. The color difference is defined in CIE 1976 UCS as $\Delta u'v' = \sqrt{(u' - u'_0)^2 + (v' - v'_0)^2}$, in which u' and v' are the actual chromaticity coordinates, while u'_0 and v'_0 are the desired

TABLE VII
STATISTICAL DATA FROM FIG. 16

RMS Error		Luminous intensity step condition			
		(time duration for verification)			
		2,500cd	3,000cd	3,500cd	4,000cd
Radiant power (a.u.)	Red LEDs, L_R	0.1260	0.1585	0.1925	0.1940
	Green LEDs, L_G	0.0309	0.0410	0.0454	0.0508
	Blue LEDs, L_B	0.0257	0.0325	0.0375	0.0425
	Total luminous intensity, Φ (cd)	9.949	15.296	21.649	25.926

chromaticity coordinates. In order to maintain steady chromaticity coordinate outputs, $\Delta u'v'$ should be lower than the limitation of just noticeable difference [19], [35], and four-step Macadam ellipse for light source standard [36]–[38], i.e., $\Delta u'v' < 0.0035$.

Setting the correlated color temperature at $T_{CCr} = 6000$ K, two experiments were designed to verify the system performance. In the first experiment, consider the control system of Fig. 13 with the radiant power input command set as $L_C = [36.569 \ 35.988 \ 22.923]^T$, which represents the luminous intensity $\Phi_0 = 3000$ cd. At first, the corresponding average power consumption of the RGB LED luminaire was measured as 7.97 W ($P_R = 3.71$ W, $P_G = 3.00$ W, and $P_B = 1.26$ W). Then, thermal disturbances were introduced into the system by attaching a thermal resistor to the RGB LED luminaire to modify the junction temperature. The thermal powers were applied as 0 W $\rightarrow$ 5 W $\rightarrow$ 10 W $\rightarrow$ 15 W. The experimental results are shown in Fig. 15. First, the system temperature is perturbed during the experiments, as shown in Fig. 15(a). However, using the designed controller, the output radiant power L_s can follow the input command $L_C = [36.569 \ 35.988 \ 22.923]^T$, as illustrated in Fig. 15(b), despite the temperature variations. Second, from Fig. 15(c), the output luminous intensity Φ can also remain at the desired 3000 cd. Finally, the chromatic output responses shown in Fig. 15(d) indicate the color difference $\Delta u'v' < 0.002$ during the experiments. In addition, the system H_∞ norm gives the superior ratio of the output two-norm to the input two-norm (i.e., the input energy) [28]. Therefore, the color difference $\Delta u'v'$ tends to be larger when the applied thermal power is larger. Furthermore, the statistical data of Fig. 15 are illustrated in Table VI, in which the rms errors of the radiant power and total luminous intensity remained relatively small, even with the thermal disturbances. Therefore, the designed controller is effective in regulating the luminous intensity and the chromaticity coordinate outputs.

For the second experiment, the feedforward compensator M was added (see Fig. 1) such that the system outputs can follow the luminous intensity commands. First, the input was set to change from 2500 to 4000 cd with an interval of 500 cd. Using the proposed control structure, the output luminous intensity can track the input, as shown in Fig. 16(a). Second, the color differences was within the limitation ($\Delta u'v' = < 0.0035$), as

illustrated in Fig. 16(b). Third, the corresponding radiant power L_s follows the corresponding radiant power from the function of (13), as shown in Fig. 16(c). Finally, Fig. 16(d) illustrated the temperature variations during the experiments. From these results, the proposed control structure was damned effective, i.e., the system responses can track the commands despite the temperature perturbations. Table VII summarizes the statistical data of Fig. 16, and showed excellent system performance using the designed robust controller and feedforward compensator M .

V. CONCLUSION

This paper has proposed a novel control structure for an RGB LED lighting system, in which a lookup table was used as the feedforward control to compensate for the variation of junction temperature. First, the RGB LED luminaire was modeled as a multivariable system with three submodels, whose transfer functions were then experimentally identified. By selecting the nominal plants, the system variations were regarded as system uncertainties and disturbances that were treated by the proposed robust controllers. Second, robust controllers were designed to guarantee system stability and performance using suitable weighting functions. In practice, the tolerances of LEDs can be experimentally tested to design suitable H_∞ robust controllers for system stability and performance. Finally, the designed controller was implemented for experimental verification. From the results, the proposed control structure and controller design were shown to be effective. It is noted that the designed robust controllers are relatively simple compared to other advanced control algorithms, and the feedback control structure can be easily miniaturized by a microprocessor, which costs less than three US dollars, as shown in [33].

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Multivariable Robust Control for a Red–Green–Blue LED Lighting System

Fu-Cheng Wang, *Member, IEEE*, Chun-Wen Tang, and Bin-Juine Huang

Abstract—This paper proposes a novel control structure for a red–green–blue (RGB) LED lighting system, and applies multivariable robust control techniques to regulate the color and luminous intensity outputs. RGB LED is the next-generational illuminant for general lighting or liquid crystal display backlighting. The most important feature for a polychromatic illuminant is color adjustability; however, for lighting applications using RGB LEDs, color is sensitive to temperature variations. Therefore, suitable control techniques are required to stabilize both luminous intensity and chromaticity coordinates. In this paper, a robust control system was proposed for achieving luminous intensity and color consistency for RGB LED lighting in a three-step process. First, a multivariable electrical–thermal model was used to obtain RGB LED luminous intensity, in which a lookup table served as a feedforward compensator for temperature and power variations. Second, robust control algorithms were applied for feedback control design. Finally, the designed robust controllers were implemented to control the luminous and chromatic outputs of the system. From the experimental results, the proposed multivariable robust control was damned effective in providing steady luminous intensity and color for RGB LED lighting.

Index Terms—Color difference, luminous intensity, red–green–blue (RGB) LEDs, robust control, thermal–electrical–luminous model.

I. INTRODUCTION

RECENTLY, LED has been drawing much attention as a state-of-the-art illuminator because of its numerous advantages, including energy savings, long lifetime, and environmental friendliness. Red–green–blue (RGB) LEDs can provide a wide color gamut for liquid crystal display (LCD) backlighting, as well as full color adjustability for general lighting applications [1], [2]. This newly developed illuminant is the only light source currently capable of this type of vivid and dynamic lighting performance. However, the tunable light outputs have been found to induce light consistency issues for RGB LED lighting, because the luminous intensity and color outputs are easily influenced by junction temperature variations caused by self-heating of the LEDs and disturbances in ambient temperatures. Therefore, proper control strategies are required to stabilize light output in order to counteract temperature variations.

To control RGB LED lighting systems, the selection of feedback signals is an important issue. Muthu *et al.* [3]–[5] applied three kinds of feedback system: color coordinate feedback with temperature feedforward (CCFB and TFF), color coordinate feedback (CCFB), and flux feedback with temperature feedforward (FFB and TFF). The color coordinates were measured by photodiodes with color filters and the fluxes with photodiodes with a time-division method. In addition, the heat sink temperature and thermal resistance were used to estimate junction temperature for temperature feedforward compensation. Hoelen *et al.* [6]–[8] further discussed light outputs and applied four control structures, namely, flux feedback, temperature feedforward, CCFB, and FFB and TFF. Among these, CCFB and FFB and TFF were shown to provide better color consistency for RGB LED lighting than did the others, when the system was experiencing junction temperature variations. Until now, CCFB has been a popular choice for application to control system design [9]–[13] because of its simple structure. However, the accuracy of feedback signals is limited by the difference between the spectra of filtered sensor and color matching functions. In contrast, the FFB and TFF structure can provide more signals for control design, but requires double loops and information about the junction temperature. For controller design, traditional control methodologies such as proportional–integral (PI) or PI derivative (PID) based algorithms have been applied to control RGB LED lighting systems [5], [7], [14], [15]. However, these methods cannot guarantee the stability and performance of systems with perturbations such as varying input power or junction temperatures. Therefore, advanced control strategies should be considered for improving system performance. In this paper, a novel control structure is proposed, and robust control techniques are applied, to achieve consistent luminous intensity and color. The effect will be experimentally verified.

The paper is arranged as follows. In Section II, an RGB LED luminaire is modeled as a multivariable system and a feedback control structure is proposed. In Section III, robust control strategies are introduced for multivariable controller design. Then, the designed controller is implemented for performance analysis in Section IV. Finally, some conclusions are drawn in Section V.

II. SYSTEM DESCRIPTION AND MODELING

A. System Description

To regulate the color and luminous intensity of RGB LED lighting, a novel control structure is proposed, as shown in Fig. 1. In this structure, T_{CCR} and Φ_r , respectively, represent the correlated color temperature (CCT) and total luminous intensity commands, while Φ is the luminous intensity output. Using

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Fig. 1. Control structure of the RGB LED lighting system (solid lines: scalar signals; mesh lines: 3×1 vector signals).

Fig. 2. Illustration of multiphysical phenomenon for RGB LED luminaire.

a lookup table M , the commands are converted to the corresponding radiant power signal $L_C = [L_{CR} \ L_{CG} \ L_{CB}]^T$, in which the subscripts “R,” “G,” and “B,” respectively, represent the “red,” “green,” and “blue” components of the signal. The controller K is used to calculate a suitable electrical power $P_E = [P_R \ P_G \ P_B]^T$ according to the error signal e . Furthermore, the dynamics of the RGB LED luminaire are modeled as G_E , with the output of luminous intensity $\Phi_{LED} = [\Phi_R \ \Phi_G \ \Phi_B]^T$. The summation matrix U is defined as $U = [1 \ 1 \ 1]_{1 \times 3}$ such that the total luminous intensity Φ is the combination of individual luminous intensity, i.e., $\Phi = U\Phi_{LED} = \Phi_R + \Phi_G + \Phi_B$.

The RGB LED luminaire is a lighting fixture composed of multiple RGB LED lamps. The RGB color LEDs can be operated by three individual electrical power sources to emit photons for lighting and simultaneously generate heat to raise junction temperature. Then the photons can stimulate retinas to produce luminous and chromatic perception, as illustrated in Fig. 2.

The electrical power P_E can be normalized as $0 \leq P_E \leq 1$, compared to the maximum power, and further divided into the following two terms:

$$P_E = P_T + P_O \quad (1)$$

Fig. 3. Electrical—thermal—luminous model.

where P_T is the normalized thermal power for heat generation and P_O is the normalized optical power for lighting. Therefore, P_T and P_O can be represented as

$$P_T = (I - \alpha) P_E \quad (2)$$

$$P_O = \alpha P_E \quad (3)$$

where α is the diagonal power factor matrix, which represents the quantum efficiency of the LEDs.

Therefore, the LED luminaire model G_E can be described as a combination of three submodels, namely, the electrical–thermal (E - T) model H , the electrical–luminous (E - L) model E_P , and the thermal–luminous (T - L) model E_T , as illustrated in Fig. 3, in which the luminous intensity Φ_{LED} is expressed as

$$\Phi_{LED} = \Phi_P + \Phi_T = E_P P_E + E_T T_j = (E_P + E_T H) P_E \quad (4)$$

where $T_j = [T_R \ T_G \ T_B]^T$ is the junction temperature, i.e., the dynamic model of G_E can be represented as

$$G_E = \frac{\Phi_{LED}}{P_E} = E_P + E_T H. \quad (5)$$

The three submodels of the RGB LED luminaire can be derived by the input–output relation. First, the E - T model H represents the influence of junction temperature by the thermal power P_T as in the following relation:

$$\Delta T_j = H P_E = \begin{bmatrix} H_{RR} & H_{GR} & H_{BR} \\ H_{RG} & H_{GG} & H_{BG} \\ H_{RB} & H_{GB} & H_{BB} \end{bmatrix} \begin{bmatrix} P_R \\ P_G \\ P_B \end{bmatrix} \quad (6)$$

where ΔT_j represents the variation of junction temperature. Second, the T - L model E_T represents the luminous intensity variation by the junction temperature as follows:

$$\Phi_T = E_T \Delta T_j = \begin{bmatrix} E_{TR} & 0 & 0 \\ 0 & E_{TG} & 0 \\ 0 & 0 & E_{TB} \end{bmatrix} \begin{bmatrix} \Delta T_R \\ \Delta T_G \\ \Delta T_B \end{bmatrix}. \quad (7)$$

Third, the E - L model E_P represents the luminous intensity variation by optical power P_O as in the following:

$$\Phi_P = E_P P_E = \begin{bmatrix} E_{PR} & 0 & 0 \\ 0 & E_{PG} & 0 \\ 0 & 0 & E_{PB} \end{bmatrix} \begin{bmatrix} P_R \\ P_G \\ P_B \end{bmatrix}. \quad (8)$$

Fig. 4. Illustration of RGB LED driving circuits.

B. System Identification of RGB LED Luminaire

The RGB LED luminaire system was used for system identification. As illustrated in Fig. 4, five RGB LED lamps [16] were installed on a 900-g aluminum heat sink (see Fig. 2) to allow the junction temperature variation by self-heating to be kept small through good thermal design. Four lamps were packaged in the front side for lighting, while the fifth was combined with a silicon photodiode [17] and assembled inside the luminaire to measure the junction temperature and radiant power (i.e., the fifth LED was used as sensors) [18]. In addition, each LED was driven by a 350 mA constant dc pulsewidth modulation (PWM), whose switching frequency was set at 120 Hz to avoid flick perception [18], [19]. According to the duty cycle commands, the normalized irreducible tensorial matrix (NITM) data acquisition (DAQ) system generated corresponding transistor-transistor logic (TTL) PWM signals, which were then connected to MOSFETs to drive the LEDs. Three independent circuits were used for power operation and measurement of the RGB LEDs through the DAQ system. The electrical power P_E could be decided by the duty cycles of the PWM signals.

The junction temperature could be estimated by the inside LED lamp using the pulse forward voltage method [20]–[23]. At first, given a 1 mA constant current input for 50 μ s, the temperature-sensitive parameter S_T is obtained from the experiments by comparing the junction temperature and the voltage output as follows:

$$S_T = \begin{bmatrix} S_{TR} & 0 & 0 \\ 0 & S_{TG} & 0 \\ 0 & 0 & S_{TB} \end{bmatrix} = \begin{bmatrix} 1.82 & 0 & 0 \\ 0 & 5.90 & 0 \\ 0 & 0 & 2.20 \end{bmatrix} \times 10^{-3}. \quad (9)$$

Therefore, the junction temperature T_j can be estimated by measuring the average forward voltage $V_{LOW} = [V_R \ V_G \ V_B]^T$ at the OFF interval of dc PWM by using 1 mA constant current, as in the following:

$$T_j = S_T V_{LOW}. \quad (10)$$

Meanwhile, the radiant powers of RGB LEDs can be measured by the silicon photodiode using the time-division method, in which the sensed radiant power $L_S = [L_R \ L_G \ L_B]^T$ is calculated by the photodiode response, given time-shift PWM

TABLE I
EXPERIMENTAL RESULTS OF PHOTODIODE MODEL

Exp.	Power (%)			Exp.	Power (%)			Exp.	Power (%)		
	P_G	P_B	S_{DR}		P_R	P_B	S_{DG}		P_R	P_G	S_{DB}
R1	20	14	0.0291	G1	60	14	0.0213	B1	60	20	0.1085
R2	25	21	0.0285	G1	70	21	0.0212	B2	70	25	0.1079
R3	30	28	0.0285	G1	80	28	0.0211	B3	80	30	0.1069
Average: 0.0287				Average: 0.0212				Average: 0.1077

Fig. 5. Experiment responses of Φ versus L_R .

Fig. 6. Apparatus for measurement and data logging of total luminous intensity, correlative color temperature, and chromaticity coordinate in CIE 1976 UCS.

signals, as [4]

$$L_S = S_D \Phi_{LED} = \begin{bmatrix} S_{DR} & 0 & 0 \\ 0 & S_{DG} & 0 \\ 0 & 0 & S_{DB} \end{bmatrix} \Phi_{LED} \quad (11)$$

in which the photodiode model S_D was obtained from the experiments, as illustrated in Table I. For example, in experiment R1, the electrical power for the green and blue LEDs was fixed at $P_G = 20\%$ and $P_B = 14\%$. Then, the electrical power for the red LED was changed from $P_R = 50\%$ to $P_R = 90\%$. The corresponding luminous intensity Φ and the sensed radiant power L_R were measured, as shown in Fig. 5, to model $L_R = S_{DR} \Phi_R = 0.0291 \Phi_R$ using the linear regressive method. Note that the variation of Φ equals the variation of Φ_R since

Fig. 7. Experimental response of electrical-thermal model H_{RR} . (a) Time-domain responses. (b) Frequency-domain responses.

176 $\Phi = \Phi_R + \Phi_G + \Phi_B$. In Table I, S_{DR} from the three experi-
 177 ments (R1, R2, and R3) are similar, such that an average value
 178 $S_{DR} = 0.0287$ was selected to represent the model. Similarly,
 179 S_{DG} and S_{DB} were experimentally obtained as follows:

$$S_D = \begin{bmatrix} S_{DR} & 0 & 0 \\ 0 & S_{DG} & 0 \\ 0 & 0 & S_{DB} \end{bmatrix} = \begin{bmatrix} 0.0287 & 0 & 0 \\ 0 & 0.0212 & 0 \\ 0 & 0 & 0.1077 \end{bmatrix}. \quad (12)$$

180 A set of instruments was built to measure the luminous and
 181 chromatic outputs of the system. As illustrated in Fig. 6, the
 182 polychromatic light output was projected into an integrating
 183 sphere for color mixing, such that the total luminous intensity Φ
 184 could be measured by the photopic detector. In addition, the light
 185 spectrum was acquired by a spectrometer to allow calculation of
 186 CCT T_{CC} and chromaticity coordinate W in Cleveland Institute
 187 of Electronics (CIE) 1976 uniform chromaticity scale (UCS)
 188 [19]. A personal computer was used for process control and
 189 data logging.

191 The dynamics of the RGB LED luminaire G_E can be ob-
 192 tained by the identification of the three submodels in (6)–(8).
 193 First, for the E - T model H , the experiments were carried
 194 out as in the following. At first, the maximum power was
 195 set as $P_{E,max} = [1.21 \ 2.56 \ 1.27]^T$ W for a single RGB
 196 LED lamp, and the normalized operation power was set as
 197 $P_E = [30 \ 30 \ 30]^T$ %. Then, step perturbations of P_R , P_G ,
 198 and P_B were applied, in turn, as system inputs, and the corre-
 199 sponding junction temperature variations were measured as sys-
 200 tem outputs. For example, Fig. 7(a) illustrates the system output
 201 of the experiment R1 (with a step input P_R from 30% to 65%).
 202 Therefore, H_{RR} can be obtained by the Rake's method [24] as
 203 follows:

$$H_{RR}(s) = \frac{0.0659(s + 0.00153)}{(s + 0.00083)}.$$

204 The experimental time-domain data were transferred to fre-
 205 quency domain by the fast Fourier transform (FFT) and com-
 206 pared with the bode plot of $H_{RR}(s)$, as illustrated in Fig. 7(b).
 207

208 From the comparison of time-domain and frequency-domain
 209 responses in Fig. 7, the first-order model is sufficient to capture
 210 the basic system dynamics, as discussed in [25]. The results of
 211 system identification at different operating points are illustrated
 212 in Table II.

213 The T - L model E_T represents the transmission path from
 214 junction temperature to luminous intensity, which can be de-
 215 scribed as a constant gain due to the short lifetime of pho-
 216 tons [26], [27]. The identification was conducted at different
 217 operating points, as illustrated in Table III, where the heat sink
 218 was heated by a thermal pad. The identification results obtained
 219 by measuring the junction temperature and the corresponding
 220 luminous intensity are shown in Table III. Fig. 8 illustrates the
 221 variation of E_{TR} at the three operating conditions.

222 Similarly, the E - L model E_P represents the transmission
 223 path from electrical power P_E to luminous intensity, which can
 224 also be considered a constant gain [26], [27]. The experiments
 225 were the same as the previous identification of E_T , but with
 226 the electrical power P_E and luminous intensity as system inputs
 227 and outputs, respectively. The operating points and identification
 228 results are illustrated in Table IV. Fig. 9 illustrates the variations
 229 of E_{PR} at the six operating conditions.

C. Feedforward Compensator

230 The feedforward compensator M is a lookup table for con-
 231 verting the CCT T_{CCr} and total luminous intensity Φ_r inputs
 232 into the corresponding radiant power L_C at different junction
 233 temperature T_j and nominal input power P_E in order to main-
 234 tain consistent light output. Therefore, the multidimensional
 235 function M can be described as
 236

$$L_C = M(T_{CCr}, \Phi_r, T_j, P_E) \quad (13)$$

237 such that the radiant power vector L_C is determined by the
 238 inputs T_{CCr} and Φ_r , and the operating conditions T_j and P_E .
 239 In experiments, the values of M are measured at many operat-
 240 ing points, and finally, decided upon by using the interpolation
 241 method. For example, Table V illustrates the relations of L_C to
 242 T_{CCr} and Φ_r [18].

TABLE II
IDENTIFICATION RESULTS OF THE ELECTRICAL-THERMAL MODEL H

Step P_R (%)	NO.	H_{RR}			NO.	H_{RG}			NO.	H_{RB}		
		pole	zero	gain		pole	zero	gain		pole	zero	gain
30→65	1	-0.00083	-0.00153	0.0659	5	-0.00083	-0.00229	0.0268	9	-0.00082	-0.00212	0.0264
65→100	2	-0.00080	-0.00227	0.0318	6	-0.00074	-0.00236	0.0259	10	-0.00073	-0.00221	0.0247
100→65	3	-0.00088	-0.00231	0.0320	7	-0.00081	-0.00181	0.0326	11	-0.00084	-0.00189	0.0293
65→30	4	-0.00083	-0.00156	0.0671	8	-0.00083	-0.00224	0.0283	12	-0.00084	-0.00222	0.0260
Step P_G (%)	NO.	H_{GR}			NO.	H_{GG}			NO.	H_{GB}		
		pole	zero	gain		pole	zero	gain		pole	zero	gain
30→65	13	-0.00087	-0.00368	0.0577	17	-0.00087	-0.00157	0.1853	21	-0.00083	-0.00167	0.1204
65→100	14	-0.00085	-0.00342	0.0562	18	-0.00084	-0.00124	0.2834	22	-0.00085	-0.00171	0.1104
100→65	15	-0.00085	-0.00316	0.0603	19	-0.00085	-0.00126	0.2794	23	-0.00086	-0.00179	0.1075
65→30	16	-0.00073	-0.00347	0.0549	20	-0.00073	-0.00141	0.1819	24	-0.00075	-0.00185	0.1051
Step P_B (%)	NO.	H_{BR}			NO.	H_{BG}			NO.	H_{BB}		
		pole	zero	gain		pole	zero	gain		pole	zero	gain
30→65	25	-0.00080	-0.00297	0.0372	29	-0.00082	-0.00256	0.0400	33	-0.00075	-0.00128	0.1095
65→100	26	-0.00083	-0.00245	0.0406	30	-0.00078	-0.00197	0.0447	34	-0.00080	-0.00112	0.1703
100→65	27	-0.00085	-0.00346	0.0318	31	-0.00084	-0.00245	0.0404	35	-0.00085	-0.00121	0.1691
65→30	28	-0.00079	-0.00317	0.0340	32	-0.00079	-0.00208	0.0458	36	-0.00081	-0.00129	0.1135

TABLE III
IDENTIFICATION RESULTS OF THE THERMAL-LUMINOUS MODEL E_T

P_R (%)	E_{TR} (cd / °C)	P_G (%)	E_{TG} (cd / °C)	P_B (%)	E_{TB} (cd / °C)
90.0	-12.88	35.0	-4.65	35.0	-0.68
70.0	-10.09	25.0	-3.09	21.0	-0.54
50.0	-7.32	15.0	-1.62	7.0	-0.33

III. ROBUST CONTROL DESIGN

From the previous identification results, the model variation was noted and should be considered for the controller design. Robust control is well known for its ability to cope with system variations and disturbances. Therefore, in this section, robust control strategies will be introduced. From the analyses of gap metrics and coprime factorization, a robust controller is designed that provides the maximum stability bound for the RGB LED lighting system. The resulting controller will then be implemented and experimentally verified in Section IV.

Fig. 8. Experimental response of the thermal-luminous model ETR.

Theorem 1 (Small Gain Theorem [28]): Suppose that $Z \in RH_\infty$ and let $\gamma > 0$. Then, the interconnected system shown in Fig. 10 is well posed and internally stable for all $\Delta(s) \in RH_\infty$ with: 1) $\|\Delta\|_\infty \leq 1/\gamma$ if and only if $\|Z(s)\|_\infty < \gamma$ and 2) $\|\Delta\|_\infty < 1/\gamma$ if and only if $\|Z(s)\|_\infty \leq \gamma$, where $\|Z\|_\infty$ is the ∞ norm of system Z .

TABLE IV
IDENTIFICATION OF ELECTRICAL-LUMINOUS MODEL E_P

T_R	E_{PR}	T_G	E_{PG}	T_B	E_{PB}
(°C)	(cd/(% P_R))	(°C)	(cd/(% P_G))	(°C)	(cd/(% P_B))
40	14.200	40	67.510	40	10.229
45	14.899	45	68.837	45	10.288
50	15.572	50	69.487	50	10.340
55	16.237	55	70.111	55	10.397
60	16.911	60	70.638	65	10.466
65	17.650	65	71.085	65	10.530

TABLE V
PARTIAL LOOKUP TABLE OF RADIANT POWER FOR RED LEDs

Radiant power of Red LEDs, L_R (a.u.)	Total luminous intensity Φ_r (cd)				
	2,000	2,500	3,000	3,500	4,000
4,000	29.462	36.841	44.221	51.600	58.979
CCT, 5,000	27.750	34.700	41.650	48.600	55.551
T_{CCr} , 6,000	26.017	32.533	39.050	45.566	52.082
(K) 7,000	24.264	30.342	36.419	42.496	48.574
8,000	22.491	28.124	33.738	39.391	45.024

Assume that a nominal plant G_0 can be expressed as $G_0 = \tilde{M}^{-1}\tilde{N}$, where: 1) $\tilde{M}, \tilde{N} \in RH_\infty$ and 2) $\tilde{M}\tilde{M}^* + \tilde{N}\tilde{N}^* = I\forall\omega$. This is called the *normalized left coprime factorization* of G_0 . In addition, suppose that a perturbed system G_Δ is represented as

$$G_\Delta = (\tilde{M} + \Delta_{\tilde{M}})^{-1} (\tilde{N} + \Delta_{\tilde{N}}) \quad (14)$$

with $\|[\Delta_{\tilde{M}} \ \Delta_{\tilde{N}}]\|_\infty < \varepsilon$ and $\Delta_{\tilde{M}}, \Delta_{\tilde{N}} \in RH_\infty$. Considering the control structure of Fig. 11, the system transfer function can be rearranged as follows:

$$\begin{aligned} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} &= \begin{bmatrix} K \\ I \end{bmatrix} (I - G_0 K)^{-1} M^{-1} \\ \omega &= \begin{bmatrix} K \\ I \end{bmatrix} (I - G_0 K)^{-1} [I \ G_0] \omega \\ \omega &= [\Delta_{\tilde{M}} \ \Delta_{\tilde{N}}] \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}. \end{aligned} \quad (15)$$

Therefore, from Theorem 1, the closed-loop system remains internally stable for all $\|[\Delta_{\tilde{M}} \ \Delta_{\tilde{N}}]\|_\infty < \varepsilon$ if and only if

$$\left\| \begin{bmatrix} K \\ I \end{bmatrix} (I - G_0 K)^{-1} [I \ G_0] \right\|_\infty \leq \frac{1}{\varepsilon}. \quad (16)$$

Furthermore, the stability margin of the system can be defined as follows.

Fig. 9. Experimental response of the electrical-luminous model E_{PR} .

Fig. 10. Illustration of small gain theorem.

Fig. 11. Block diagram of the perturbed plant G_Δ with controller K .

Definition 1 (Stability Margin [29]): The stability margin $b(G, K)$ of the closed-loop system is defined as

$$b(G, K) = \left\| \begin{bmatrix} K \\ I \end{bmatrix} (I - GK)^{-1} [I \ G] \right\|_\infty^{-1}. \quad (17)$$

Hence, from Theorem 1, the closed-loop system is internally stable for all $\|[\Delta_{\tilde{M}} \ \Delta_{\tilde{N}}]\|_\infty < \varepsilon$ if and only if $b(G, K) \geq \varepsilon$. However, the coprime factorization of a system may not be unique. Hence, the gap between two systems G_0 and G_Δ is defined as follows.

Definition 2 (Gap Metric [28]): The smallest value of $\|[\Delta_{\tilde{M}}, \Delta_{\tilde{N}}]\|_\infty$ that perturbs G_0 into G_Δ is called the gap between G_0 and G_Δ , and is denoted by $\delta(G_0, G_\Delta)$.

From the definitions, $b(G, K)$ gives the radius (in terms of gap metric) of the largest ball of plants stabilized by the controller K . Therefore, the goal of the controller design is to derive a suitable controller K from a nominal plant G_0 , such that all perturbed plants G_i located inside the gap $\delta(G_0, G_i) < \varepsilon$ will satisfy $b(G, K) \geq \varepsilon$ and the closed-loop system will remain internally stable, i.e., the variations (tolerances) of LEDs can be experimentally tested in the manufacturing processes, and

used to design suitable robust controllers that can guarantee the system stability.

A. Selection of the Nominal Plant

The selection of the nominal plant G_0 for the RGB LED luminaire was based on the system gaps between all transfer functions of G_E such that the maximum gap is minimized as

$$\min_{G_0} \max_{G_i} \delta(G_0, G_i) \quad (18)$$

where G_i represents all possible models of G_E . Considering (5), where $G_E = E_P + E_T H$ with the models of H , E_P , and E_T at all operating conditions, it can be derived that $\delta(G_0, G_i) \leq \delta(E_{P0}, E_{Pi}) + \delta(E_{T0}H_0, E_{Ti}H_i)$. Furthermore, it is noted that $\delta(E_{P0}, E_{Pi}) \leq 0.0075$ from Table III, and $\delta(E_{T0}H_0, E_{Ti}H_i) \leq 0.3748$ from Tables I and II, (*) shown at the bottom of this page.

Therefore, $\delta(G_0, G_i) \leq \delta(E_{P0}, E_{Pi}) + \delta(E_{T0}H_0, E_{Ti}H_i) = 0.3823$ with the following nominal plant $G_0 = E_{P0} + E_{T0}H_0$ for the RGB LED luminaire: shown (19) at the bottom of this page.

Note that the maximum gap can be regarded as the maximum system perturbation due to the variation of operating conditions, such as the input power P_E and the junction temperature T_j .

B. Controller Synthesis

The design procedures of the robust controller can be illustrated as follows [30]–[33].

1) *Loop-shaping design*: The nominal plant G_0 is shaped by precompensator W_1 and postcompensator W_2 to form a shaped plant $G_s = W_2 G W_1$, as shown in Fig. 12(a).

Fig. 12. Design procedures of robust controllers.

Fig. 13. Simplified RGB LED lighting control system for robust controller design.

2) *Robust stabilization estimate*: The maximum stability margin $b_{\max}$ is defined as

$$b_{\max}(G_s, K) \triangleq \inf_{K \text{ stabilizing}} \left\| \begin{bmatrix} K \\ I \end{bmatrix} (I - G_s K)^{-1} \begin{bmatrix} I & G_s \end{bmatrix} \right\|_{\infty}^{-1} \quad (20)$$

where M_s and N_s are the normalized left coprime factorization of G_s , i.e., $G_s = \tilde{M}_s^{-1} \tilde{N}_s$. If $b_{\max}(G_s, K) \ll 1$, then one must return to step (1) to modify W_1

$$H_0 = \begin{bmatrix} \frac{0.0659(s + 0.00153)}{(s + 0.00083)} & \frac{0.0577(s + 0.00368)}{(s + 0.00087)} & \frac{0.0318(s + 0.00346)}{(s + 0.00085)} \\ \frac{0.0268(s + 0.00229)}{(s + 0.00083)} & \frac{0.1853(s + 0.00157)}{(s + 0.00087)} & \frac{0.0404(s + 0.00245)}{(s + 0.00084)} \\ \frac{0.0264(s + 0.00212)}{(s + 0.00082)} & \frac{0.1204(s + 0.00167)}{(s + 0.00083)} & \frac{0.1691(s + 0.00121)}{(s + 0.00085)} \end{bmatrix}$$

$$E_{T0} = \begin{bmatrix} -10.09 & 0 & 0 \\ 0 & -3.09 & 0 \\ 0 & 0 & -0.54 \end{bmatrix} \quad E_{P0} = \begin{bmatrix} 15.572 & 0 & 0 \\ 0 & 67.510 & 0 \\ 0 & 0 & 10.229 \end{bmatrix}. \quad (*)$$

$$G_0(s) = \begin{bmatrix} \frac{14.9071(s + 0.00153)}{(s + 0.00083)} & \frac{-0.5822(s + 0.00368)}{(s + 0.00087)} & \frac{-0.3209(s + 0.00346)}{(s + 0.00085)} \\ \frac{-0.0828(s + 0.00229)}{(s + 0.00083)} & \frac{66.9374(s + 0.00157)}{(s + 0.00087)} & \frac{-0.1248(s + 0.00245)}{(s + 0.00084)} \\ \frac{-0.0143(s + 0.00212)}{(s + 0.00082)} & \frac{-0.0650(s + 0.00167)}{(s + 0.00083)} & \frac{10.1377(s + 0.00121)}{(s + 0.00085)} \end{bmatrix}. \quad (19)$$

Fig. 14. Implementation of RGB LED lighting control system. (a) Illustration of the control structure. (b) Layouts of the experimental instruments. (c) Experimental settings.

Fig. 15. Experimental responses to constant radiant power inputs with thermal disturbances. (a) Temperature variations. (b) Radiant power responses L_S . (c) Total luminous intensity Φ . (d) Color difference in CIE 1976 UCS $\Delta u'v'$.

and W_2 . Then, an $\varepsilon \leq b_{\max}(G_s, K)$ is selected to synthesize a stabilizing controller K_∞ , which satisfies $\left\| \begin{bmatrix} K_\infty \\ I \end{bmatrix} (I - G_s K_\infty)^{-1} \begin{bmatrix} I & G_s \end{bmatrix} \right\|_\infty^{-1} \geq \varepsilon$, as shown in Fig. 12(b).

3) Finally, the designed controller K_∞ is multiplied by the weighting functions, i.e., $K = W_1 K_\infty W_2$, and implemented to control system G , as illustrated in Fig. 12(c).

In Fig. 1, the compensator M converted the commands T_{CCr} and Φ_r into corresponding radiant power signal L_C . Therefore, the controller design can be simplified as Fig. 13, in which the nominal plant of the RGB LED luminaire is defined as $\bar{G}_0 = S_D G_0$. Using the aforementioned controller design techniques, the optimal H_∞ robust controller was designed as

$$K(s) = \begin{bmatrix} -0.4196 & 0.0098 & 0.0047 \\ 0.0146 & -1.4141 & 0.0047 \\ 0.0135 & 0.0122 & -1.0898 \end{bmatrix} \quad (21)$$

with a stability bound $b(\bar{G}_0, K) = 1$, which is much larger than the system gap. Therefore, the controller can stabilize the system even with plant perturbations. However, the steady state of L_S due to a unit step input $L_C = [1 \ 1 \ 1]^T$ can be calculated as

TABLE VI
STATISTICAL DATA FROM FIG. 15

RMS Error		Thermal disturbance (time duration for verification)			
		0W (250s-500s)	5W (750s-1000s)	10W (1250s-1500s)	15W (1750s-2000s)
Radiant power (a.u.)	Red LEDs, L_R	0.1806	0.1821	0.1878	0.1991
	Green LEDs, L_G	0.0496	0.0472	0.0480	0.0509
	Blue LEDs, L_B	0.0362	0.0356	0.0364	0.0369
Total luminous intensity Φ (cd)		2.641	4.094	5.151	5.532

follows:

$$\lim_{t \rightarrow \infty} L_S(t) = \lim_{s \rightarrow 0} s \bar{G}_0 K (I + \bar{G}_0 K)^{-1} \frac{1}{s} = [1.1072 \ 1.0075 \ 1.0696]^T$$

i.e., there is steady-state error due to a unit step input. Therefore, the following weighting function with integrals was used to

Fig. 16. System responses to a serial luminous intensity step input. (a) Total luminous intensity. (b) Color difference in CIE 1976 UCS. (c) Radiant power. (d) Temperature variation.

eliminate the steady-state error [34]:

$$W_1(s) = \frac{1}{s} \begin{bmatrix} \frac{1}{0.4196} & 0 & 0 \\ 0 & \frac{1}{1.4141} & 0 \\ 0 & 0 & \frac{1}{1.0898} \end{bmatrix}.$$

Using the loop-shaping techniques with $G_s = \bar{G}_0 W_1$, the robust controller was design as

$$K'(s) = W_1 K_\infty = \frac{1}{s} \begin{bmatrix} -2.3832 & 0.0042 & -0.0031 \\ -0.0012 & -0.7072 & -0.0020 \\ 0.0012 & 0.0026 & -0.9176 \end{bmatrix}$$

with a stability bound $b(\bar{G}_0, K') = 0.7071$, which was smaller than in the previous design (1), but still much larger than the maximal system gap (0.3823). However, the integral terms can guarantee zero steady-state error of the system due to step inputs, i.e., the use of W_1 sacrificed a little stability bound, but guaranteed zero steady-state errors to a step command. Therefore, the choice of weighting functions was a compromise between system performance and stability specifications. In the next section, the designed controller K' will be implemented for experimental verification.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental setup of the RGB LED lighting control system is illustrated in Fig. 14. Fig. 14(a) illustrates the control structure in which the measurement and control signals were transmitted through a DAQ system, NI PCI6229, to the PC-based controller. Fig. 14(b) shows the experimental layouts for the control loop (on the left) and data measurement (on the right) to verify the output luminous and chromatic properties. The overall experimental settings are illustrated in Fig. 14(c). For controller implementations, $K'(s)$ was first converted into discrete time as in the following:

$$K'(z) = \frac{1}{z-1} \begin{bmatrix} -0.2383 & 0.0004 & -0.0003 \\ -0.0001 & -0.0707 & -0.0002 \\ 0.0001 & 0.0003 & -0.0918 \end{bmatrix}$$

with a sampling time $T = 0.1$ s. During the experiments, the CCT T_{CC0} was set at 6000 K. Implemented with the controller K' , the system performance can be discussed by the rms error of the luminous intensity and the color difference of chromaticity coordinate outputs, which should be as small as possible. The color difference is defined in CIE 1976 UCS as $\Delta u'v' = \sqrt{(u' - u'_0)^2 + (v' - v'_0)^2}$, in which u' and v' are the actual chromaticity coordinates, while u'_0 and v'_0 are the desired

TABLE VII
STATISTICAL DATA FROM FIG. 16

<i>RMS Error</i>		Luminous intensity step condition			
		(time duration for verification)			
		2,500cd	3,000cd	3,500cd	4,000cd
Radiant power (a.u.)	Red LEDs, L_R	0.1260	0.1585	0.1925	0.1940
	Green LEDs, L_G	0.0309	0.0410	0.0454	0.0508
	Blue LEDs, L_B	0.0257	0.0325	0.0375	0.0425
	Total luminous intensity, Φ (cd)	9.949	15.296	21.649	25.926

chromaticity coordinates. In order to maintain steady chromaticity coordinate outputs, $\Delta u'v'$ should be lower than the limitation of just noticeable difference [19], [35], and four-step Macadam ellipse for light source standard [36]–[38], i.e., $\Delta u'v' < 0.0035$. Setting the correlated color temperature at $T_{CCr} = 6000$ K, two experiments were designed to verify the system performance. In the first experiment, consider the control system of Fig. 13 with the radiant power input command set as $L_C = [36.569 \ 35.988 \ 22.923]^T$, which represents the luminous intensity $\Phi_0 = 3000$ cd. At first, the corresponding average power consumption of the RGB LED luminaire was measured as 7.97 W ($P_R = 3.71$ W, $P_G = 3.00$ W, and $P_B = 1.26$ W). Then, thermal disturbances were introduced into the system by attaching a thermal resistor to the RGB LED luminaire to modify the junction temperature. The thermal powers were applied as 0 W $\rightarrow$ 5 W $\rightarrow$ 10 W $\rightarrow$ 15 W. The experimental results are shown in Fig. 15. First, the system temperature is perturbed during the experiments, as shown in Fig. 15(a). However, using the designed controller, the output radiant power L_s can follow the input command $L_C = [36.569 \ 35.988 \ 22.923]^T$, as illustrated in Fig. 15(b), despite the temperature variations. Second, from Fig. 15(c), the output luminous intensity Φ can also remain at the desired 3000 cd. Finally, the chromatic output responses shown in Fig. 15(d) indicate the color difference $\Delta u'v' < 0.002$ during the experiments. In addition, the system H_∞ norm gives the superior ratio of the output two-norm to the input two-norm (i.e., the input energy) [28]. Therefore, the color difference $\Delta u'v'$ tends to be larger when the applied thermal power is larger. Furthermore, the statistical data of Fig. 15 are illustrated in Table VI, in which the rms errors of the radiant power and total luminous intensity remained relatively small, even with the thermal disturbances. Therefore, the designed controller is effective in regulating the luminous intensity and the chromaticity coordinate outputs.

For the second experiment, the feedforward compensator M was added (see Fig. 1) such that the system outputs can follow the luminous intensity commands. First, the input was set to change from 2500 to 4000 cd with an interval of 500 cd. Using the proposed control structure, the output luminous intensity can track the input, as shown in Fig. 16(a). Second, the color differences was within the limitation ($\Delta u'v' \leq 0.0035$), as

illustrated in Fig. 16(b). Third, the corresponding radiant power L_s follows the corresponding radiant power from the function of (13), as shown in Fig. 16(c). Finally, Fig. 16(d) illustrated the temperature variations during the experiments. From these results, the proposed control structure was damned effective, i.e., the system responses can track the commands despite the temperature perturbations. Table VII summarizes the statistical data of Fig. 16, and showed excellent system performance using the designed robust controller and feedforward compensator M .

V. CONCLUSION

This paper has proposed a novel control structure for an RGB LED lighting system, in which a lookup table was used as the feedforward control to compensate for the variation of junction temperature. First, the RGB LED luminaire was modeled as a multivariable system with three submodels, whose transfer functions were then experimentally identified. By selecting the nominal plants, the system variations were regarded as system uncertainties and disturbances that were treated by the proposed robust controllers. Second, robust controllers were designed to guarantee system stability and performance using suitable weighting functions. In practice, the tolerances of LEDs can be experimentally tested to design suitable H_∞ robust controllers for system stability and performance. Finally, the designed controller was implemented for experimental verification. From the results, the proposed control structure and controller design were shown to be effective. It is noted that the designed robust controllers are relatively simple compared to other advanced control algorithms, and the feedback control structure can be easily miniaturized by a microprocessor, which costs less than three US dollars, as shown in [33].

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