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Monte Carlo analysis of a control technique for a tunable white lighting system

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A simulated colour control mechanism for a multi-coloured LED lighting system is presented. The system achieves adjustable and stable white light output and allows for system-to-system reproducibility after application of the control mechanism. The control unit works using a pre-calibrated lookup table for an experimentally realized system, with a calibrated tristimulus colour sensor. A Monte Carlo simulation is used to

examine the system performance concerning the variation of luminous flux and chromaticity of the light output. The inputs to the Monte Carlo simulation, are variations of the LED peak wavelength, the LED rated luminous flux bin, the influence of the operating conditions, ambient temperature, driving current, and the spectral response of the colour sensor. The system performance is investigated by evaluating the outputs from the Monte Carlo simulation. The outputs show that the applied control system yields an uncertainty on the luminous flux of 2.5% within a 95% coverage interval which is a significant reduction from the 8% of the uncontrolled system. A corresponding uncertainty reduction in $\Delta u'v'$ is achieved from an average of 0.0193 to 0.00125 within 95% coverage range after using the control system.

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1. Introduction

Mixed colour LED white lamps and luminaires are used widely in theatres, studio lighting, and architectural lighting due to their wide gamut, outstanding energy

efficiency[1-3], and attractive colour quality[4-6]. These systems, based on additive LED

colour mixing, present challenges regarding the stability of colour and light output

during the operation and the lifetime of the systems. The instabilities are due to

variations in colour and luminous flux of the individual LEDs that are large enough to

be perceived by human observers. These types of changes in light output can be

noticeable when comparing the illumination from similar lighting systems side by side.

The stability and the reproducibility of such lighting systems depend on both the

intrinsic properties of the LED system and the operating conditions. The intrinsic

properties, i.e. the wavelength and the luminous flux of the LEDs within the selected

bin, and the sensitivity of individual LEDs to the operating conditions, can be varied.

The abrupt failure of LEDs can also cause lumen depreciation. Dong *et al* diagnosed

lumen depreciation in multi-coloured LED systems[7], mainly due to LED failures, using a

system with photosensors which may limit the real world implementation because

many such systems use a lot of LEDs. Finally, the operating conditions themselves can

vary notably; e.g. current level, ambient temperature, junction temperature[8],

operation time, aging, etc.[9].

To keep colour and light output variations within acceptable levels for critical

applications, some form of active control of the LED system is necessary. Without

compromising the efficiency and the light quality, several methods of controlling light

have been implemented by other authors[10-21]. Temperature feedback alone can

account only for the variations of the luminous efficiency with the temperature

changes for the coloured LEDs. Thus, this feedback system is not in common practice.

On the other hand, feedback of the luminous flux alone cannot interpret the variations

with temperature of the chromaticity coordinates of the coloured LEDs. It can account

for the variations of luminous efficiency with the aging of LEDs. Therefore, the

combination of temperature feedback and luminous flux feedback are well suited for

LED colour control. The chromaticity coordinates feedback system measures the

chromaticity coordinates and at the same time as the brightness of the mixed light

produced by the LED luminaire directly. This kind of feedback system is also

appropriate for the LED colour control. Moreover, there is no strong preference for

employing either the combination of temperature feedback and luminous flux

feedback or feedback for chromaticity coordinates[22]. Application specific requirements

decide the choice of the feedback system to obtain the quantitative evaluation of the

feedback system. In this paper, we have controlled chromaticity coordinates along with

the light output of a multicoloured LED lighting system which has an application in

stage lighting. Furthermore, we have evaluated the uncertainty of the system

parameters in real time by using a Monte Carlo simulation.

In this paper, we propose an approach where we utilize a set of initially

optimized settings and a colour sensor to control the light output and chromaticity

during the operation of a multi–coloured LED lighting system. By implementing a

feedback loop based on the colour sensor readings, the control system delivers an

error correction through the optimized settings for the individual colour channels to

produce a tunable white light according to the target values of the correlated colour

temperature (CCT) and the luminous flux (Φ_V). These target values could range in CCT

from 3000 K to 6000 K with a dimming capability and in Φ_V from 1000 to 8000 lm, thus

achieving a minimum lower dimming limit of 13% for a particular CCT. Dimming below

1000 lm for that particular CCT could introduce an uncertainty from the limitations of

the LED driver electronics known as digital multiplex (DMX) control. Due to the

uncertainties in the lighting system, the light output will deviate from the target of CCT

and Φ_V. The Monte Carlo simulation process is applied to calculate the uncertainty in

the output of the LED lighting system from the influences of LED luminous flux and

wavelength bin, junction temperature, driving current, ambient temperature, DMX

control on current, and colour sensor response. The advantage of the Monte Carlo

simulation is that there is no requisite for partial derivatives of the complicated

equations or analytical propagation of uncertainty. The methodology applied here is a

combination of simulated and experimental findings of the uncertainties of individual

input parameters of the coloured LEDs. Although the present simulation shows the

influence of luminous depreciation on colour stability, in future, further simulation can

be done on the uncertainty contributions due to the unexpected failure of LEDs and

LED ageing. The probability distribution of output chromaticity parameters u', v', CCT,

D_{uv}, and Φ_V are used to evaluate the uncertainties of input parameters. The control

unit uses an incorporated, pre-calibrated lookup table for an initial estimate and then

evaluates the result by using a calibrated tri-colour sensor for monitoring the

chromaticity of the light output. After that, the control unit utilizes the lookup table

and the colour sensor output to set a new set of driving currents to the individual

colour channels by choosing a new lookup entry. The stability of the chromaticity is

quantified by using the CIE method for evaluating white light sources[23] which uses the

$\Delta u'v'$ distance in the CIE 1976 uniform chromaticity diagram.

2. Methods

We propose a new method that permits the regulation of colour and luminous flux

while minimizing erroneous variations for a particular system using knowledge of a

generic lighting system. The method incorporates a pre–calibrated lookup table that

employs a rule-based optimization of chromaticity distance from the Planckian locus

(D_{uv}) for the original CCT and Φ_V settings. The calibrated colour sensor, monitoring the

tristimulus values (*X*, *Y*, *Z*) is applied to provide feedback from the light output. The

Monte Carlo simulation is used to provide the statistical analysis of the uncertainties on

the output parameters resulting from the uncertainties on the input parameters to the

multicolored LED lighting system. A schematic diagram of the control system is shown

in Figure 1. The whole control mechanism is divided into two sections: 1) the top-left is

called the control algorithm; 2) the middle section is showing the hardware

connections to the control unit. The right section of Figure 1 presents the statistical

analysis of the input parameters and their corresponding influences to the control

mechanism while the bottom-left evaluates the Monte Carlo output. The following

sections explain the procedures of the control unit in detail.

2.1 Pre-calibrated lookup table

We initially mixed the spectral radiant flux of four coloured LEDs (royal blue,

blue, red, and green) with a warm white LED. The additive colour mixing process

supplements and changes the spectral power distribution (SPD) of the white LED. This

multi-coloured light engine is described in Chakrabarti *et al*[24]. The spectral radiant flux

of the coloured LED is calibrated from the spectral measurements of the individual

coloured LED at various settings of the controllable parameters (operating current,

junction temperature, etc.)[25]. In Figure 2, we illustrate two resultant SPDs – shown with

the black line, which are the outputs for two of the target CCTs (3000 K and 5800 K,

respectively) at 8000 lumens. In Figure 2, the purple line represents the reference

SPDs, which for CCT ≤ 5000 K is represented by a Planckian radiator SPD and for CCT >

5000 K is represented by the corresponding D–illuminant SPD. The other coloured SPDs

in Figure 2 show the contribution from individual colour channels to create the

resultant SPD. The lookup table is set up with a novel algorithm. The Table uses the

reference SPDs, to find the target CCTs (3000 K to 6000 K in 1% step size of the previous

CCT) and the corresponding target Φ_V (1000 lm to 8000 lm in 3% step size of the

previous Φ_V) with an optimized D_{uv}. The target colour settings for the light output are

also optimized by the general colour rendering index (CRI) R_a > 85 and the particular

CRI R_9 > 40 for rendering red objects. The target point in the lookup table offers

information about the corresponding DMX values for the individual colour channels for

the LED light engine as described in Chakrabarti et al[24].

2.2 Colour control

To operate the LED lighting system, the user would have to set the target CCT to a

value between (3000 K and 6000 K) and the luminous flux Φ_V to a value between (1000

lm and 8000 lm) [Figure 1]. The control unit then finds a match in the lookup table

closest to the target values. In the ideal case, the lighting system delivers the target by

using the corresponding DMX values of individual colour channels from that lookup

point. The aforementioned uncertainty contributors inside the lighting system

influence the light output. Unlike the analytical analysis, the uncertainty analysis of

multi-coloured LEDs can be done by the Monte Carlo simulation process with an

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iteration $N=2000$[26].

We use the Monte Carlo simulation to investigate the colorimetric and photometric variations of the spectral light output as output ($u´$, $v´$, and corresponding CCT, D_{uv}, and Φ_V) based on the uncertainties generated from the lighting system as input to the Monte Carlo simulation [Figure 1]. These input uncertainties are measured experimentally or are adopted from data sheet values. With this methodology, similar but varying lighting systems, utilizing e.g. other LED bins and environmental conditions, can be controlled without doing any additional calibrations. The control system explained in Aldrich *et al*[21] did not consider the aforementioned uncertainty parameters inside their lighting system to produce the optimized lighting solution. In our paper the colour sensor has been used to monitor the CCT, Φ_V, and D_{uv} variations in real-time and receives the feedback from the light output (Figure 1). The intensity dimming of our system is quicker than the aforementioned system. The used colour sensor has approximate tristimulus responsivity of the colour matching functions ($\bar{x}$, $\bar{y}$, and $\bar{z}$) and needs to be calibrated close to the operating chromaticity range to minimize the spectral mismatch errors. The colour sensor was calibrated by using a handheld spectrometer (GS-1150)[27].

After obtaining the measured tristimulus values of the resulting white light, the control algorithm calculates the corresponding CCT$_{Measure}$, $\Phi_{V\ Measure}$, and $D_{uv\ Measure}$ from the tristimulus values. After that, the CCT$_{Measure}$, and the $\Phi_{V\ Measure}$ are subtracted from

the CCT$_{Target}$, and the $\Phi_{V\,Target}$, respectively. These differences are then added to the target values to obtain CCT$_{Corrected}$ and $\Phi_{V\,Corrected}$ (seen Equations (1) and (2)). The closest values of the CCT and the Φ_V to the CCT$_{Corrected}$, and the $\Phi_{V\,Corrected}$ are then found in the lookup table.

$$CCT_{Corrected} = CCT_{Target} + (CCT_{Target} - CCT_{Measure}) \qquad (1)$$

$$\Phi_{V\,Corrected} = \Phi_{V\,Target} + (\Phi_{V\,Target} - \Phi_{V\,Mrasure}) \qquad (2)$$

The new lookup point provides the corrected driving information for the individual colour channels to deliver a corrected light output, which is seen in the result section to be closer to the target CCT and Φ_V values. The lookup table already has the optimized D_{uv} values ($\pm 2 \cdot 10^{-3}$) for each lookup point. However, the large variation in D_{uv} may need an extra D_{uv} correction. In that case, the D_{uv} needs to be corrected using the individual colour sensitivity to D_{uv}. If the obtained D_{uv} shows a higher value than the desired D_{uv} value, the green channel needs to decrease along with adding more from red and/or blue channels depending on the CCT region. For a negative D_{uv} correction, the green channel needs to increase while the red and/or blue channel needs to drive less than the previous settings. The white channel can increase/decrease to adjust the Φ_V. Finally, after the D_{uv} correction, the changes in

driving currents of the respective colour channels lead to a new lookup point, which is evaluated by plotting on the CIE 1976 (u´,v´) diagram[23]. We cannot control colour rendering indices[28] (such as R_a, R_9) by the proposed control technique. However, the pre-calibrated lookup table already has been spectrally optimized to R_a >85 and R_9 >40. Thus, the controlled light output has a good light quality regarding colour rendering according to the application. The control mechanism can be generalized to be used in any other solid state lighting system where instead of using the colour sensor, a spectrometer may be employed for obtaining the spectral information.

3. Results and discussion

As mentioned earlier, there is a challenge in getting a stable light output from a multi-coloured LED lighting system due to the different performances of the LEDs under the same operating conditions which are the inputs for the Monte Carlo simulation. Using the Monte Carlo method to simulate the variation of input parameters of individual LEDs internally for N=2000 iterations, the uncertainties in the colour quantities ($u´$, $v´$, CCT, D_{uv}, Φ_V, R_a and R_9) in light output are obtained as output from the Monte Carlo simulation. To achieve colour quantities, the Monte Carlo simulation results in 2000 simulated resultant SPDs for the 2000 iterations (acting as 2000 virtual lighting systems). Due to the uncertainties in the system, those 2000 SPDs are different to the

target SPD, resulting in variations in the CCT, Φ_V, and D_{uv}. The simulated light output for tuning range from 3500 K to 6000 K and shows an average of 8% change on Φ_V within a 95% coverage interval over an initial setting of 8000 lm due to the uncertainties of the input parameters if the ambient temperature changes from 20°C to 45°C.

We have taken 5500 K and 8000 lm as target CCT and Φ_V, respectively (as seen in Figure 1) to illustrate the colour variations in the uncontrolled multi-coloured LED lighting system. The Monte Carlo method was then applied to the target SPD to add changes due to uncertainty contributors for the 2000 iterations. From the resulting 2000 SPDs, the chromaticity coordinates ($u´,v´$) are calculated. The probability distributions of variations in CCT and D_{uv} for the 2000 iterations are derived from ($u´$, $v´$) and are shown in Figure 3(a)-(b). The coverage interval of 95% from the distribution implies ΔCCT = 940 K with an arithmetic mean of 5709 K and ΔD_{uv} = 0.0252 with an arithmetic mean of 0.0028, and are represented by the green colour in the same figure. In Figure 3(c) and (d) we have plotted the corresponding probability distributions of variations in CRI R_a and R_9 derived from the SPD of the light output from the Monte Carlo analysis. Within the 95% coverage interval, indicated by green lines, we have found the CRI variation of ΔR_a = 15.4 with an arithmetic mean of 91 and a change of ΔR_9 = 95.7 with an arithmetic mean of 43, respectively. These high values of the colour rendering indices come from the spectral optimization algorithm, used for generating the pre-calibrated lookup table. Similarly, the coverage interval of 95% $\Delta \Phi_V$

is equal to 704 lm with an arithmetic mean of 8170 lm. We have evaluated the

uncontrolled output parameters of CCT, D_{uv}, and Φ_V from the Monte Carlo simulations

for target CCT settings from 3500 K to 6000 K with a target Φ_V of 8000 lm. ΔCCT, ΔD_{uv},

ΔR_a, ΔR_9, and $\Delta \Phi_V$ are large for the uncontrolled lighting system [Figure 3]. Thus, the

observer can perceive the colour variations as well as light output variations. However,

these variations can be narrowed down within a certain limit after implementing the

control mechanism as described in the Method section (Figure 1). Table 1 shows the

variations in CCT, D_{uv}, and Φ_V for the uncontrolled lighting system compared with those

of the controlled system. The Table shows six target CCT settings from 3500 K to 6000 K

while all are at a target of Φ_V = 8000 lm. The uncontrolled ΔCCT, ΔD_{uv}, and $\Delta \Phi_V$ are high

at a target CCT of 3500 K. This is because, at a target CCT of 3500 K, the contribution

from the uncertainties due to the red LEDs are higher than for the other target CCTs.

From the Table, it can be seen that the stabilized system decreases the average

uncertainty within a 95% coverage interval on luminous flux from 8% to 2.5%. The

reduction in chromaticity from the uncontrolled system of average 0.0193 and to the

controlled system is of average 0.00125 in $\Delta u'v'$ within 95% coverage range. Similarly,

the controlled system reduces the uncertainty on the CCT at 5500 K from 940 K to 133

K. The corresponding maximum D_{uv} variation is reduced from 0.025 to 0.001 at 5500 K.

Similar values are found at the other target CCTs.

Figure 4 shows the distribution of the four parameters for the 2000 iterations

after implementing the control system at a target CCT of 5500 K. The green lines show the distribution within a 95% coverage interval. Figure 4(a) and (b) indicate that the variations of CCT and D_{uv} have been reduced to ΔCCT = 133 K and ΔD_{uv}=0.0011 within the 95% coverage interval. Similarly, Figure 4(c) and (d) show ΔR_a = 0.18 and ΔR_9=4.9 within 95% coverage range.

However, when the user insists on exceeding the delivery capability of the luminaire, the control system cannot provide solutions within the tolerance region of the target luminous flux. Table 2 demonstrates the simulated results of a target CCT at 3000 K while the target luminous fluxes are 4000 lm and 8000 lm, respectively, for uncontrolled and controlled lighting systems. In that table, for the target value 4000 lm, the control system provides controlled Φ_V with 2.2% variations over the 95% coverage interval. However, for the target value = 8000 lm, the solutions of Φ_V lie within 5% variations over the 95% coverage range because all the red LEDs were not performing at the required level.

Table 3 shows the simulated results for the accepted luminous flux depreciation of each colour LED implemented in the present control system. The Table also indicates the maximum number of admitted LED failures during the controlling operation. The considered amount of LED failures among 210 LEDs is 4% in total. In future, to handle more abrupt failure and luminous flux depreciation, each LED needs to be operated at a maximum of 80% of its available power.

Figure 5 indicates the effective performance of the control system by showing

the colour variations of 2000 iterations in the CIE 1976 (u', v') diagram before and after

having the colour control applied to the lighting system. In Figure 5, the deviations in

D_{uv} (ΔD_{uv}) are seen as the distance from a given point to the daylight locus (black solid

line). The variations in CCT (ΔCCT) are found as the distance to the isothermal line

(black dash lines). A just noticeable chromaticity difference at 50% probability is

considered to be 0.0013 in (u', v') coordinates, corresponding to $n = 1.1$[23]. This

definition is usable in the white operating region which is investigated here. Figure 5

shows a Just Noticeable Difference (JND) circle at $n = 1.18$, and a circle with a radius of

double that of the JND circle corresponding to $n = 2.36$. Here the centre of the circle is

the target CCT = 5494 K, and $D_{uv} = 5.89 \cdot 10^{-4}$ (purple triangle).

It is clear that the target position is indicating an offset from the daylight locus.

This offset is because the lookup values are not optimized to D_{uv} at zero, rather; they

are optimized to D_{uv} at $\pm 2 \cdot 10^{-3}$ as recent findings show that the human preference for

D_{uv} favours an optimum D_{uv} that might not be at zero D_{uv}[29,30]. From Figure 5, it is

observed that the found solutions before implementing the control system (gray dots)

are almost outside the just noticeable chromaticity difference circle (solid red) and

they are not closer to the target point. Similarly, the green 'o' implies the solutions for

those 2000 iterations after implementing the control system in Figure 5. It is observed

from Figure 5 that 95% of the controlled chromaticities are within a circle of n=2.36,

hence the colour control system can narrow down the variations along the daylight locus (ΔCCT) as well as along the isothermal line (ΔD$_{uv}$). The system is not able to control all the chromaticities within the JND circle.

The present lookup table has two dimensions for ranges of target values in CCT and Φ_V, where the targets represent an optimized D_{uv} value ($\pm 2 \cdot 10^{-3}$). Here we have used a separate D_{uv} correction separate from the lookup table.   Future work may improve the controlled solutions by implementing a three-dimensional lookup table by adding a range of D_{uv} values.

Figure 6 describes the simulated results of the control system for the range of CCTs of the lighting system at Φ_V = 8000 lm. The CCT of the lighting system is tunable from 3000 K to 6000 K with a step of 100 K. The red solid 'dot' data points represent the controlled CCT point obtained as a solution at the corresponding target CCT. The relation between them is linear with a coefficient of determination R^2 = 0.999. The controlled luminous flux found at the corresponding target CCT is denoted by the blue solid "square" data points, while the dashed black line is showing the target: Φ_V = 8000 lm. The variation in luminous flux at 8000 lm, for the CCT ranging from 3000 K to 6000 K is within ~1.8 %. The control mechanism can be validated by experimental LED colour mixing systems with colour sensors installed to demonstrate both the system stability and the system-to-system reproducibility determined visually and by spectro-radiometric measurements.

Figure 7 shows the influence of lumen depreciation on $\Delta u'v'$ at a target CCT of 3500 K, 4500 K, and 5500 K where the simulated luminous depreciation is employed for every LED. The graph indicates that 50% of the observers may not notice the colour change if the lumen depreciation is within a 5% of each used LED from the rated luminous flux of the individual LED. However, Figure 7 also implies that the colour change will be significantly noticeable from 7.5% of lumen depreciation of each used LED from the rated luminous flux of the individual LED at 5500 K.

The application note of MAZet[31] used the true colour sensor to monitor the LED colour for multi-coloured LED lighting systems which could be a closer approach to our work. They found, at the neutral CCT (4500 K), the optimization can improve to a $\Delta u'v'$ = 0.0021. In our lighting system, the simulation shows that the improvement of a $\Delta u'v'$ is to 0.0018 within the 95% coverage range at 4500 K.

4. Conclusions

Although multi-coloured LED lighting systems are popular nowadays, they often suffer from poor colour stability and reproducibility from system-to-system due to colour and luminous flux variation. We propose a methodology for stabilizing a five–coloured LED lighting system by introducing a colour control algorithm inside the system, covering a wide white gamut to achieve chromaticity and luminous flux stability during operation.

The LED lighting system produces a tunable white light output; with CCTs ranging from 3000 K to 6000 K with a luminous flux dimming capability for each CCT setting. The implemented colour control is a combination of a pre-calibrated lookup table for CCT and Φ_V in combination with a calibrated tristimulus colour sensor for luminous flux and chromaticity control. Additional D_{uv} correction is needed and implemented to bring the output variations near the just noticeable limit.

The colour control system performance is analyzed by using a Monte Carlo simulation process. This process simulates the SPD of the mixed light output based on stochastic variations in the input parameters: LED flux and wavelength bin, junction temperature, driving current, ambient temperature, driver electronics, and colour sensor spectral response. For the stimulated SPD variations, and hence variations in CCT, D_{uv} and Φ_V (as the outputs of the Monte Carlo process) the colour sensor provides real-time feedback of the light output. The pre-calibrated lookup table is made by spectral optimization of SPD over a range of CCT values and luminous flux values covering the operational range for a particular LED lighting system. It is based on the spectral measurements of five-coloured LED channels and the optimized settings of low D_{uv} ($\pm 2 \cdot 10^{-3}$), a general colour rendering index (CRI) of $R_a > 85$, and a particular CRI $R_9 > 40$.

The control system has been shown to be able to regulate the light output and chromaticity. At 5500 K, D_{uv} variations are reduced from approximately 0.025 to 0.001.

The controlled stabilizing system decreases the average uncertainty of luminous flux from 8% to 2.5% and similarly reduces the corresponding chromaticity from the uncontrolled system average 0.0193 to the controlled system average 0.00125 in $\Delta u'v'$ by using a 95% coverage interval. We have thus shown that with our methodology, similar but varying lighting systems, utilizing other LED bins and environmental conditions, can be controlled to within chromaticity variations corresponding to twice the JND, without doing any additional calibrations.

References

1. Kim JK, Schubert EF. Transcending the replacement paradigm of solid-state lighting. *Optics Express* 2008; 16(26): 21835–21842.

2. De Almeida A, Santos B, Paolo B, Quicheron M. Solid state lighting review – potential and challenges in Europe. *Renewable and Sustainable Energy Reviews* 2014; 34: 30–48.

3. US Department of Energy. *LED Basics*. 2016. Retrieved from: http://energy.gov/eere/ssl/led-basics

4. Oh JH, Yang SJ, Sung Y-G, Do YR. Excellent color rendering indexes of multi-package white LEDs. *Optics Express* 2012; 20(18): 20276.

5. Lei J, Gu X, Liu M. Spectral assemblage using LEDs to obtain specified characteristics. *Applied Optics* 2014; 53(35): 8151–8156.

6. Zhang M, Chen Y, He G. Color temperature tunable white-light LED cluster with extra high color rendering index. *Scientific World Journal* 2014; 9: 897960.

7.   Dong J, Pandharipande A, Van Driel W, Zhang G. Diagnosing lumen depreciation in LED lighting systems: An estimation approach. *IEEE Transactions on Signal Processing* 2012; 60(7): 3796–3808.

8.   Chhajed S, Xi Y, Li YL, Gessmann T, Schubert EF. Influence of junction temperature on chromaticity and color-rendering properties of trichromatic white-light sources based on light-emitting diodes. *Journal of Applied Physics* 2005; 97: 1–8.

9.   OSRAM. *Reliability and Lifetime of LEDs.* 2013. Retrieved   from: http://www.osram-os.com/Graphics/XPic6/00102625_0.pdf

10.   Nimz T, Hailer F, Jensen K. Sensors and feedback control of multi-colour LED systems. *LED Professional Review* 2012; 32: 46-49.

11.   Robinson S, Ashdown I. Polychromatic optical feedback control, stability, and dimming. In: *Proceedings of the SPIE*, 2006: pp. 633714-633714–10.

12.   Man K, Ashdown I. Accurate colorimetric feedback for RGB LED clusters. In:

Proceedings of the SPIE, 2006: pp. 633702–1.

13. Sisto MM, Gauvin J. Accurate chromatic control and color rendering optimization in LED lighting systems using junction temperature feedback. In: *Proceedings of the SPIE*, 2014: pp. 919002.

14. He G, Tang J. Spectral optimization of color temperature tunable white LEDs with excellent color rendering and luminous efficacy. *Optics Letters* 2014; 39(19): 5570–5573.

15. Li H, Mao X, Han Y, Luo Y. Wavelength dependence of colorimetric properties of lighting sources based on multi-color LEDs. *Optics Express* 2013; 21(3): 3775–3783.

16. Liu Z, Liu S, Wang K, Luo X. Optical analysis of color distribution in white LEDs with various packaging methods. *IEEE Photonics Technology Letters* 2008; 20(24): 2027–2029.

17. MAZeT GmbH. *True Color Management for Lighting Systems*, 2007. Retrieved from: http://www.energie-und-

technik.de/fileadmin/media/whitepaper/files/app07226e.pdf

18. Žukauskas A, Vaicekauskas R, Ivanauskas F, Gaska R, Shur MS. Optimization of white polychromatic semiconductor lamps. *Applied Physics Letters* 2002; 80(2): 234–236.

19. Ries H, Leike I, Muschaweck J. Optimized additive mixing of colored light-emitting diode sources. *Optical Engineering* 2004; 43(7): 1531.

20. Muthu S, Chang C, Bruning G. White LED luminary light control system. US 6,441,558 B1, 2002.

21. Aldrich M, Zhao N, Paradiso J. Energy efficient control of polychromatic solid state lighting using a sensor network. Tenth International Conference on Solid State Light, *Proceedings of the SPIE* 2010; 7784(1): 778408.

22. Ackermann B, Schulz V, Martiny C, Hilgers A, Zhu X. Control of LEDs. *IEEE Industrial Applications Society* 2006; 5: 2608–2615.

23. Commission Internationale de l'Eclairage. CIE TN 001:2014 *Chromaticity*

Difference Specification for Light Sources. Vienna: CIE, 2014.

24. Chakrabarti M, Pedersen HC, Petersen PM, Poulsen C, Poulsen PB, Dam-Hansen C. High-flux focusable color-tunable and efficient white-light-emitting diode light engine for stage lighting. *Optical Engineering* 2016; 55(8): doi 10.1117/1.OE.55.8.085101.

25. Chakrabarti M, Thorseth A, Corell DD, Dam-Hansen C. A white-cyan-red LED system for low correlated colour temperature lighting. *Lighting Research and Technolnology*. First published 3 August 2015, doi 1477153515608416.

26. Chakrabarti M, Thorseth A, Jepsen J, Dam-Hansen C. Monte carlo analysis of multicolour LED light engine. In: *Proceedings of the 28th CIE Session,* Manchester, UK. 28 June - 4 July 2015. Vienna: CIE: p. OP60 526.

27. Gamma Scientific. *GS-1150 Handheld Spectrophotometers*. 2015. Retrieved from: http://www.elliotscientific.com/image/data/pdf/Gamma/GS-1150_Datasheet_949.pdf

28. Commission Internationale de l'Eclairage. *Method of Measuring and Specifying*

Colour Rendering Properties of Light Sources. CIE Publication 13.3. Vienna, CIE, 1995.

29.   Rea MS, Freyssinier JP. White lighting: A provisional model for predicting perceived tint in "white" illumination. *Color Research and Application* 2014; 39: 466–479.

30.   Ohno Y, Fein M. Vision experiment on acceptable and preferred white light chromaticity for lighting. In: *CIE 2014 Lighting Quality and Energy Efficiency*, CIE Publication x039:2014. Vienna: CIE, pp. 192–199.

31.   MAZeT GmbH. *Accuracy Optimization of True Color Sensor Solutions for LED Color Control of Multiple LED Light Sources*. 2012. Retrieved   from: http://www.mazet.de/en/downloads/product-customer-information/white-paper.html

Figure captions

Figure 1. Schematic diagram of the colour control system of the multi-coloured tunable (3000 K to 6000 K) white LED lighting system

Figure 2. Resultant SPDs as the target (black line) in a five colour mixing LED system at two different target CCTs (3000 K and 5800 K in (a) – (b)) and the corresponding reference SPDs (purple line). Individual SPDs of the five coloured LEDs are also shown by different colours.

Figure 3. (a) - (d) represent the probability distributions within 95% coverage interval (green) of uncontrolled CCT, D_{uv}, CRI R_a, and R_9, respectively, for 2000 iterations while the red colour is indicating the same for outside the 95% coverage interval for a target CCT of 5500 K with Φ_V = 8000 lm.

Figure 4. (a) - (d) represent the probability distributions within 95% coverage interval (green) of controlled CCT, D_{uv}, CRI R_a, and R_9, respectively, for 2000 iterations. The red colour is indicating the same for outside the 95% coverage interval at a target CCT of 5500 K with Φ_V = 8000 lm

Figure 5. The example of uncontrolled and controlled solutions for the lighting system at 5500 K in the CIE 1976 (u'- v') diagram

Figure 6. Controlled light output from the lighting system while the CCT is tuned from 3000 K to 6000 K with 100 K resolution at 8000 lm

Figure 7. Simulated change in $\Delta u'v'$ for a target CCT of 3500 K, 4500 K, and 5500K

according to lumen depreciation in percent, for every LED of the lighting system.

Table 1. CCT, D_{uv}, and Φ_V variations within 95% coverage interval at target CCT settings with Φ_V= 8000 lm

Target CCT [K]	ΔCCT [K] (uncontrolled)	ΔCCT [K] (controlled)	ΔD_{uv} (uncontrolled)	ΔD_{uv} (controlled)	$\Delta\Phi_V$ [lm] (uncontrolled)	$\Delta\Phi_V$ [lm] (controlled)
3500	1070	43	0.0251	0.0010	785	209
4000	732	60	0.0190	0.0008	637	199
4500	742	71	0.0160	0.0013	610	190
5000	722	112	0.0189	0.0022	598	202
5500	940	133	0.0252	0.0011	704	209
6000	849	150	0.0227	0.0005	663	208

Table 2. CCT, D_{uv}, and Φ_V variations within 95% coverage interval at a target CCT = 3000 K with Φ_V= 4000 lm and 8000 lm, respectively

Target CCT [K]	Target Φ_V [lm]	ΔCCT [K] (uncontrolled)	ΔCCT [K] (controlled)	ΔD_{uv} (uncontrolled)	ΔD_{uv} (controlled)	$\Delta\Phi_V$ [lm] (uncontrolled)	$\Delta\Phi_V$ [lm] (controlled)
3000	4000	361	8	0.0067	3.8×10^{-5}	257	88
	8000	1620	6	0.0365	1.2×10^{-4}	874	380

Table 3. Luminous flux depreciation and LED failures among 210 colour LEDs

Type of LEDs	Total numbers in lighting system	Acceptable Luminous flux depreciation [%]	Acceptable number of LED failures
Royal blue	18	15.2	3
Blue	24	7.6	2
Red	12	4	0
Green	30	2.3	0
White	126	2.3	3