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A color management system for multi-colored LED lighting

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ABSTRACT

A new color control system is described and implemented for a five-color LED light engine, covering a wide white gamut. The system combines a new way of using pre–calibrated lookup tables and a rule-based optimization of chromaticity distance from the Planckian locus with a calibrated color sensor. The color sensor monitors the chromaticity of the mixed light providing the correction factor for the current driver by using the generated lookup table. The long term stability and accuracy of the system will be experimentally investigated with target tolerance within a circle radius of 0.0013 in the uniform chromaticity diagram (CIE1976).

Keywords: Solid state lighting, multi-color LEDs, uncertainty budget, light quality, light stability, color control, color sensor, product testing.

1. INTRODUCTION

The multi-colored mixed white LED lamps and luminaires are used widely in different lighting applications; namely in theaters, studio lighting, and architectural lighting because of their wide white gamut, excellent energy efficiency, and high color quality[1,2,3]. However, the LED color mixing systems often suffer from poor color and light output instability due to noticeable variations in color and luminous flux. The long term and short term stability of the color and light output are generally influenced by uncertainty contributors; namely LED binning (wavelength and flux) and ageing, ambient temperature and LED junction temperature, driver electronic such as digital control of current, etc[4]. Thus, in such applications, the color variations and the stability in short and long time use should be controlled by employing some form of feedback in the LED clusters to maintain color and light output variations within acceptable levels. In order to overcome such issues without sacrificing efficiency, several methods were adopted based on temperature feedback, flux feedback or a combination of these two techniques or color feedback[5,6,7,8].

We present an approach to obtain controlled chromaticity and stability of a multi–colored light engine over short and long term use from a set of initially optimized settings. The color control system provides intelligent control of the individual LED color arrays to produce high quality white light from the light engine ranging in correlated color temperature (CCT) between 3000 K and 5800 K with luminous flux (Φ_V) dimming from 1000 lm to 8000 lm for each CCT setting. A feedback control system combines pre-calibrated lookup tables for each CCT setting with a calibrated color sensor for chromaticity control. The calibrated color sensor monitors the chromaticity of the mixed light and also provides the correction factor for the current driver by using the lookup table. The long term stability and accuracy of the system will be experimentally investigated with a target tolerance within a certain circle radius of 0.0013 in the uniform chromaticity diagram (CIE 1976)[9]. The following section will describe the method of the color control in detail. The *Result and discussion* section will analyze the experimental results and will validate the method. The conclusion section will conclude the novelty of the mentioned color control system.

2. METHOD

In this section we describe a method that enables the use of a new color control system to make the stability in color variation and light output within a certain limit. The method combines a new way of using pre–calibrated lookup tables and a rule-based optimization of chromaticity distance from Planckian locus (D_{uv}) with a calibrated color sensor. The user firstly set the target CCT and Φ_V. Hereafter, the light engine produces light output by finding a point at the lookup table which corresponds to the CCT and Φ_V. The selected point in the lookup table provides the information about the driving current for the individual LEDs and finally, the light engine is lit up. The light output from the light engine is

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certainly not similar to the desired target values because of uncertainty contributors of the system; peak in the wavelength bin, wavelength shifts with temperature changes, flux bin, expected ageing, etc. The color sensor monitors the chromaticity of the mixed light which is corrupted by the influence of uncertainty parameters of the system as described by Chakrabarti et. al[10] and then the system provides the correction factor for the current driver by using the new generated point from the lookup table. The steps of the control system are described in the following sections.

Pre–calibrated lookup table by multicolored LED mixing engine

A pre-calibrated lookup table is generated using a new algorithm, called Ideal White Light Radiator-guided search algorithm (IWLiR), it consists of target CCTs (3000 K to 6000 K in 1% step size of the previous CCT) and corresponding target Φ_V (1000 lm to 8000 lm in 3% step size of the previous Φ_V) at optimized D_{uv} (< 2 x 10^{-3}) which is shown in Figure 1. The target CCTs are spectral mixtures characterized by a high general color rendering index (CRI) R_a > 85 and specific CRI R_9 > 40 for rendering the strong red objects e.g. skin tones.

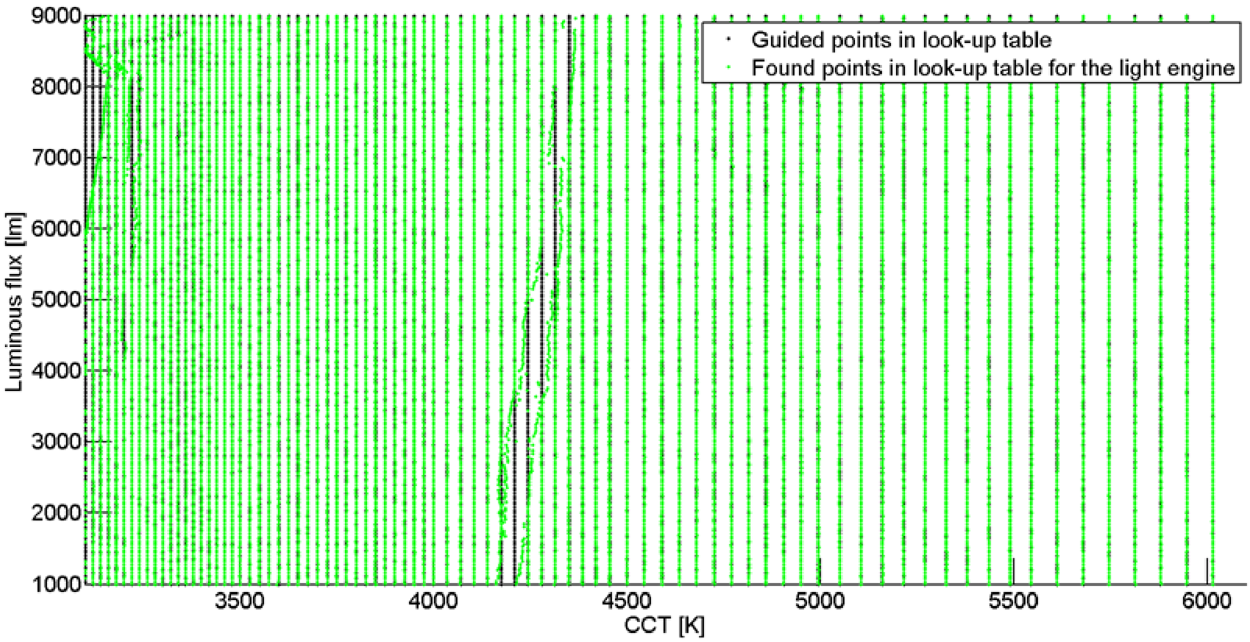

Figure 1: Pre–calibrated lookup table consists of target CCTs (3000 K to 6000 K in 1% step size of the previous CCT and corresponding target luminous flux (1000 lm to 8000 lm in 3% step size of the previous Φ_V) at optimized D_{uv} (< 2 x 10^{-3}).

Initially, the algorithm simulates the spectral radiant flux for each colored LED as input to mix the spectral content of the LED color mixing engine. The light engine is using four colored LEDs (Red, Green, Blue and Royal blue) to add the spectral power distribution (SPD) from a warm white LED at 3000 K. The output from the aforementioned individual LEDs is mixed to provide white light output from the light engine varying from 3000 K to 6000 K with Φ_V dimming from 1000 lm to 8000 lm. The IWLiR is lastly generated from the spectral calibration of the color mixing engine. After setting the target of the CCT and Φ_V as references, the IWLiR is used to find the optimum adjustments for the individual LEDs which are optimized to the lowest D_{uv}, high CRI, and as close to the target values as possible. Figure 2 shows the obtained D_{uv} and CRI (R_a) in regards to the CCT and Φ_V. The pre-calibrated lookup table within the IWLiR also provides the information about the corresponding optimized driving current for individual LEDs. In Figure 3, at a constant $\Phi_{V,}$ the CCT ranging from 3000 K to 6000 K has been illustrated for the current driving information of individual LEDs.

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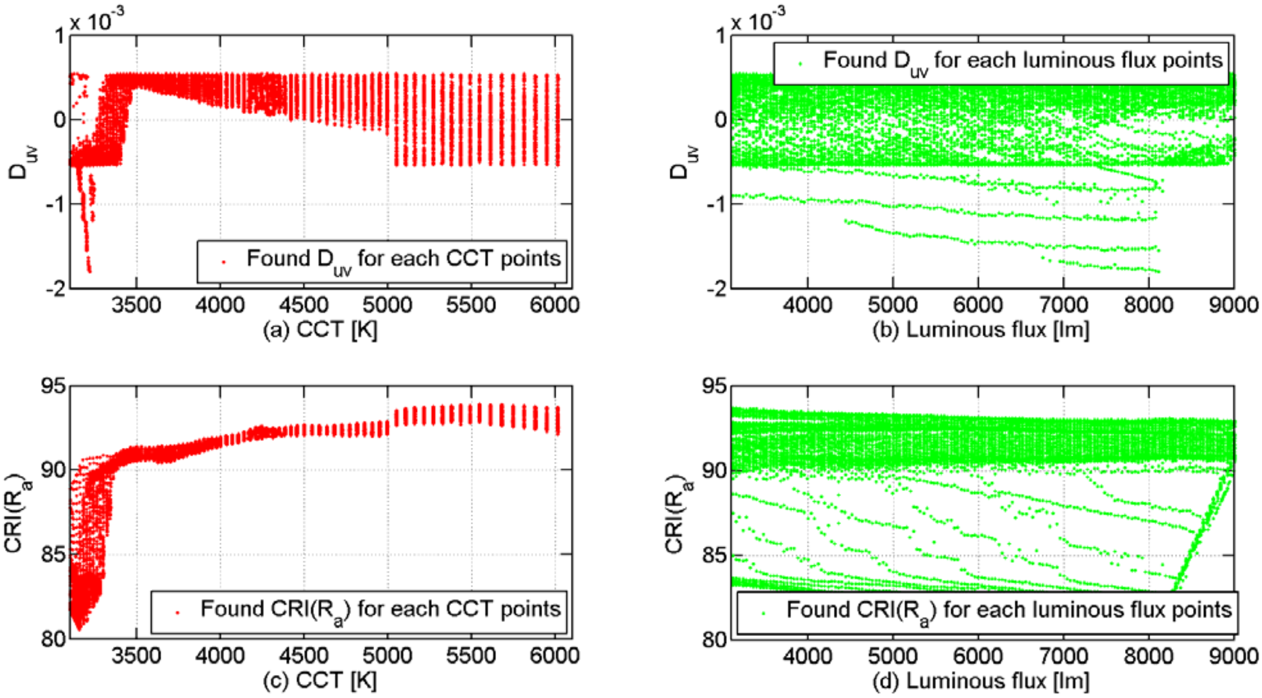

Figure 2: (a and b) Optimized Duv, (c and d) CRI (R_a) vs target CCTs and Φ_V respectively.

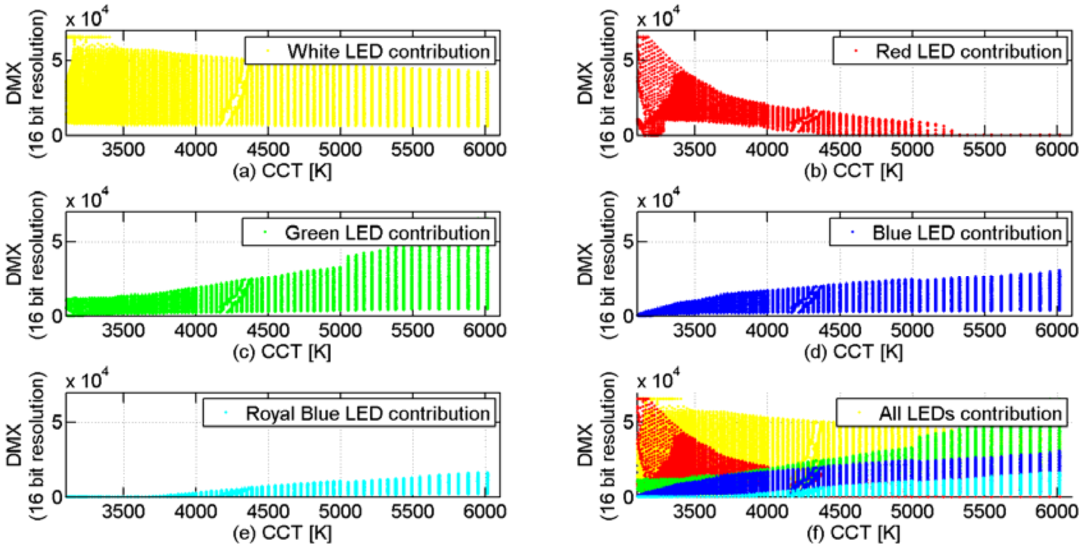

Figure 3: Corresponding driving current information for individual LEDs for target CCTs at 8000 lm.

Color control system

We have implemented a new color control system which is depicted in Figure 4. First of all, the user needs to enter the desired CCT (3000 K – 6000 K) and Φ_V (1000 lm – 8000 lm) into the system. The pre-calibrated lookup table finds the suitable point closest to the desired CCT and Φ_V values with the optimized D_{uv}. The lookup point provides the

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corresponding driving current information of the individual LEDs with which the light engine delivers the desired light output in an ideal case. Due to uncertainties in the input system parameters (LED bin, LED ageing, etc.), and ambient temperature of the light engine, the light output cannot produce the desired light output. The uncertainty analysis of multi-colored LEDs can be done by using the Monte Carlo simulation process as was reported at the CIE conference [10]. The Monte Carlo simulation process analyses the color variations (such as CCT and D_{uv}) and Φ_V based on the uncertainties in the input parameters for the light engine. These uncertainties are experimentally measured values multiplied by a factor of 20 to judge the functionality of the color control system. Introducing the perturbation on the system uncertainties enables a lamp to lamp calibration. A color sensor has been implemented to get feedback from the light output in real time to control the CCT and Φ_V variations as shown in Figure 4. Basically, after getting feedback information from the color sensor, the correction factor is fed to the control box and finally, the control box locates the new lookup point for the light engine which provides corrected driving information for the individual LEDs to deliver light output with the desired CCT and Φ_V.

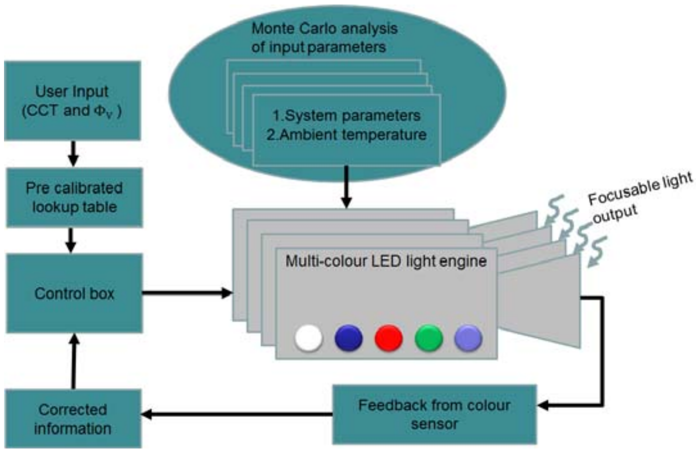

Figure 4: Block diagram of color control system.

3. RESULTS AND DISCUSSION

The results obtained thus far are discussed in this section. The graph in Figure 5 is a comparison between the three resultant SPDs obtained from a pre-calibrated lookup point (for reference), uncontrolled light output (for system uncertainty), and a new pre-calibrated lookup point (for controlled light output) at 5000 K. As shown in the graph, due to wavelength shift in the system, the SPDs for uncontrolled light and controlled light adjust correspondingly and shift in the wavelength space compared to the reference light. However, the controlled light output delivers the desired light output which is closer to the target CCT and the target Φ_V.

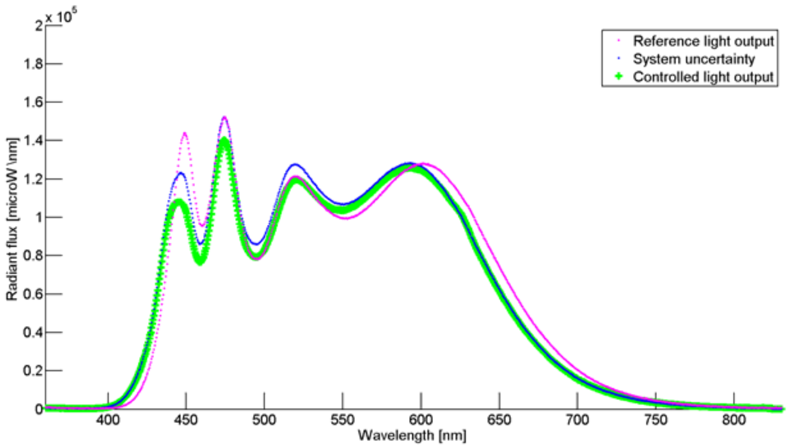

Figure 5: Compared SPDs before and after implementing the control system.

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Figure 6 is an example of testing the functionality of the implemented control system for the light engine. We have simulated the output variations in CCT and Φ_V for 200 similar kinds of systems by the uncertainty analysis using the Monte Carlo simulation described in the article of Chakrabarti et. al[10]. The purple '+' in the Figure 6 represents the desired Φ_V target at 5000 K. The blue points are the found solutions corresponding to the aforementioned target value for the 200 systems. The uncertainties in the systems cause large variations in the color space (CCT) as well as in the Φ_V (blue points). After implementing the color control system in the light engine these variations are small, represented by the green dots. Due to the uncertainty of measuring light output by color sensor as well as the uncertainty in the DMX control for the driving current, the green points cannot overlap with the target point.

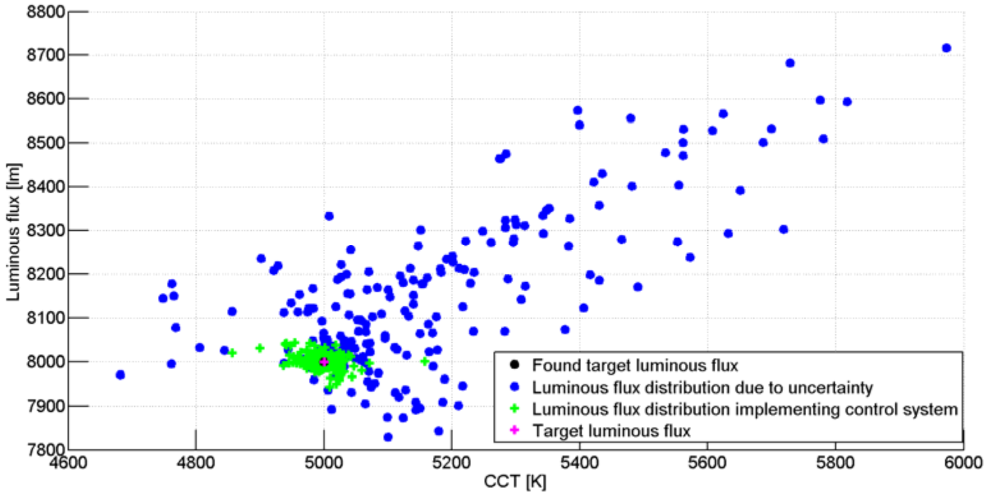

Figure 6: Illustration of the functionality of the control system in CCT vs Φ_V diagram.

Figure 7 represents the variations of Φ_V in the 200 simulated systems illustrated by blue (uncertainties in the system) and green (after implementing the control system) dots. The purple '+' represents the target Φ_V which is 8000 lm. As shown in the figure, the green dots are closer to the target value than the blue dots. This observation can be illustrated by the standard deviation of Φ_V variations which are also shown in Figure 7. The blue lines are the standard deviation (65% coverage interval) of light output due to the uncertainties in the systems and the green lines are the standard deviation (65% coverage interval) of light output after implementing the control system.

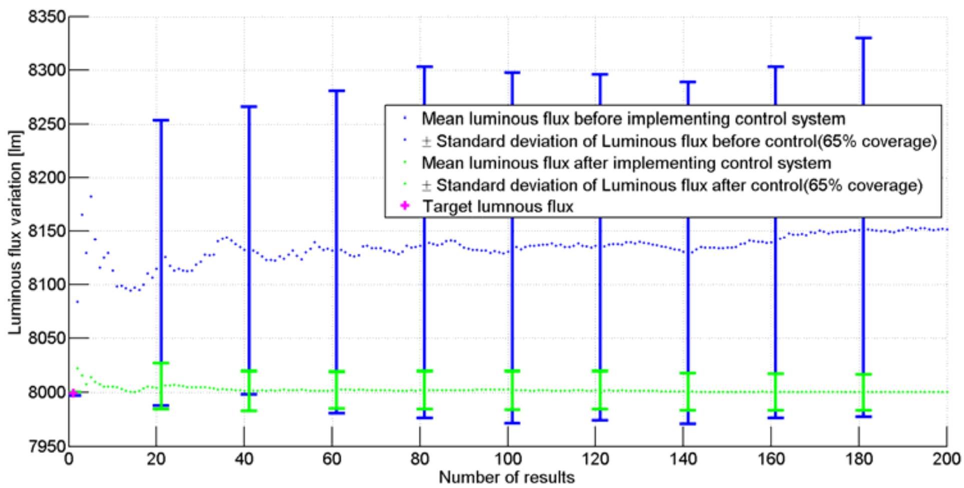

Figure 7: Comparison of Φ_V variations before and after implementing the control system.

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Figure 8 also represents the variation of CCT for the 200 systems by blue dots (uncertainties in the system) and green dots (after implementing the control system) respectively. Here, the purple '+' also represents the target CCT which is 5000 K. As the color control system controls the CCT variation up to certain limit, the green dots are closer to the target value than the blue. The standard deviation of CCT variations plotted in the Figure 8 dictates that the blue lines (65% coverage interval) of light output in the systems are larger than the green lines (65% coverage interval) of light output after implementing the control system, this is again due to the uncertainties.

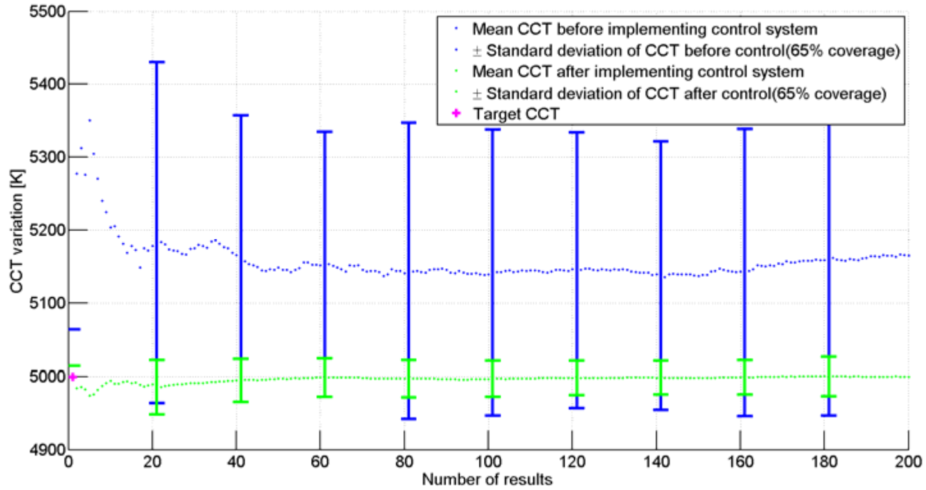

Figure 8: Comparison of CCT variations before and after implementing the control system.

As in Figure 8, a similar graph has been plotted for D_{uv} variations in Figure 9. In this case, the variations of D_{uv} after implementing the control system are larger or almost similar as the D_{uv} variations in the uncontrolled system. The control system is based on the pre-calibrated lookup table. Although the D_{uv} is optimized and low (< 5 x 10-3) for all lookup points in the lookup table, the present color control system cannot control the D_{uv} variations. Our future control system will address aforementioned issue and will control the third dimension of the color control by using the tristimulus values of the color sensor.

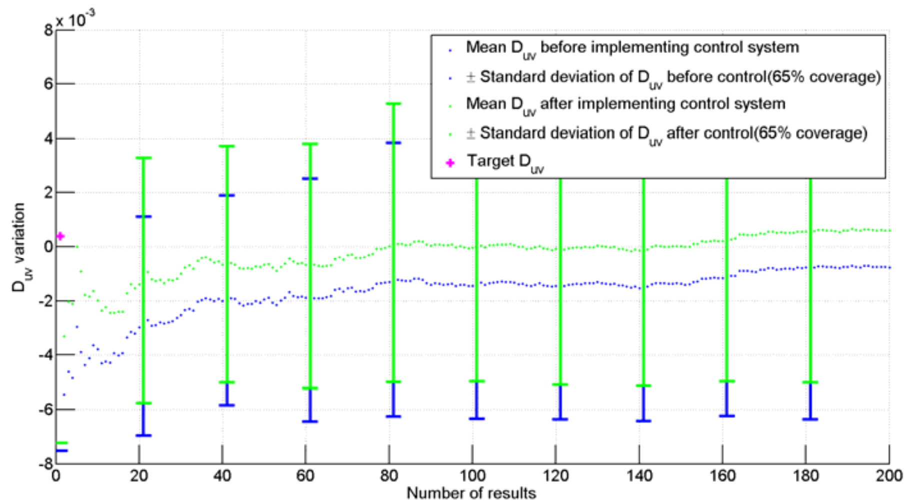

Figure 9: Comparison of D_{uv} variations before and after implementing the control system.

The following Table 1 illustrates the standard deviation comparison of Φ_V, color qualities (CCT, and D_{uv}) between before and after implementing the color control system for the target CCTs ranging from 3000 K to 6000 K at a constant

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target Φ_V = 8000 lm. As shown in Table 1 the variations of Φ_V for all target CCTs are small after implementing the control system. Similarly, the variations of CCT for all target CCTs are also small after implementing the control system except for 3000 and 3500 K. We have noticed that there are no lookup points at 3000 K with 8000 lm in the lookup table (Figure 1). The current implementation of IWLiR cannot able to find fitting solutions for all targets within the search interval. The future work will resolve this issue. As our control system is based on lookup points in the lookup table, the control system gives uncertain result at 3000 K with 8000 lm. Generally, we have noticed that the red LED is more sensitive to ambient temperature compared to other LEDs. At 3500 K the contribution from the red LED is higher than other LEDs. Thus, the variation in CCT is higher even after implementing the control system. As expected, the standard deviation in D_{uv} has not improved after implementing the control system in Table 1.

Table 1: Comparison of color quantities before and after color control is implemented in the light engine.

Target CCT [K] at D_{uv} = 0, Φ_v = 8000 [lm]	Before control			After control		
	Std. Φ_v [lm]	Std. CCT [K]	Std. D_{uv}	Std. Φ_v [lm]	Std. CCT [K]	Std. D_{uv}
3000	189.3	195.8	0.0042	17.4	180.7	0.0044
3500	191.3	194.4	0.0044	46.8	99.9	0.0045
4000	165	179	0.0042	18	20	0.0042
4500	176.4	220	0.0047	18.9	26.9	0.0052
5000	178.4	221	0.0057	16.7	28.4	0.0057
5500	186.2	225.6	0.0057	20.4	36.5	0.0052
6000	171.2	293.5	0.0057	17.8	77.4	0.0056

Figure 10 represents the color variations of 200 systems in u′v′ diagram (CIE-1976 chromaticity coordinates). The black line represents the Planckian locus and the red line represents the isothermal line for 5000 K. The variation along the Planckian locus characterizes the variation in CCT and the variation along the isothermal line describes the variation in D_{uv}. The purple dot in Figure 10 signifies the target point and the blue circle refers to the 1–step just noticeable chromaticity difference (JND) circle[9]. The cyan '+' represents the solutions for the 200 systems before implementing the control system and the green '+' implies the solutions for those 200 systems after implementing the control system. As mentioned earlier, the color control system could narrow down the variation along the Planckian locus (CCT variation) and the effect is observed in Figure 10, whereas the variation along the isothermal line (D_{uv} variation) cannot be controlled. Thus, all solutions for the 200 measured systems after color control are not identified within the area of the blue circle. The solutions which are within the blue circle of radius of 0.0013 hold a 50% probability for the variations in color not to be noticeable to the human eye. The future work on color control will eliminate the issue and the solutions after implementing the color control system is expected to identified within the blue circle of radius 0.0013.

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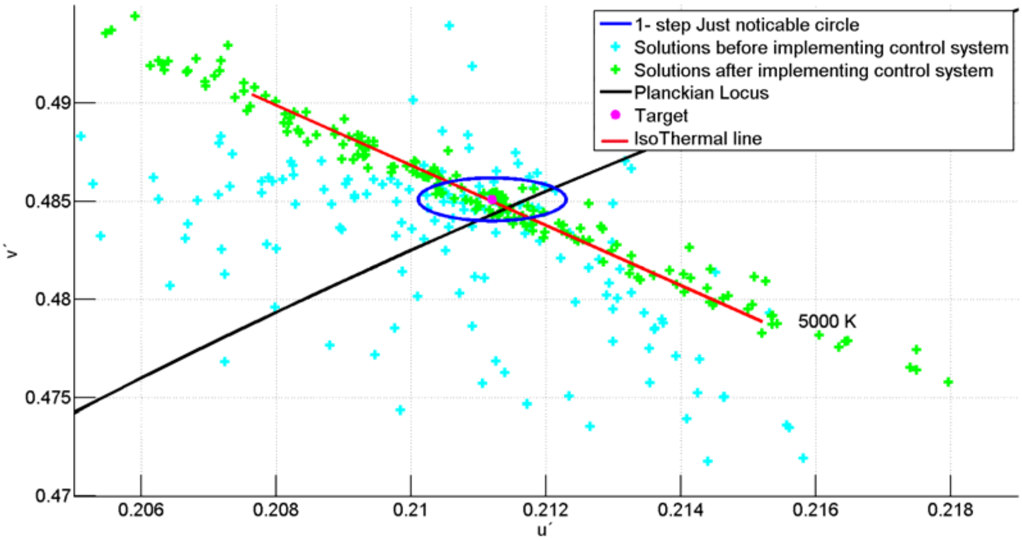

Figure 10: The functionality of the control system in u´- v´ diagram (CIE-1976 chromaticity coordinates) (axes 2.5:1).

4. CONCLUSION

The LED color mixing systems, widely used in different lighting applications, often suffer from poor color rendering and color instability. In order to overcome these problems without sacrificing efficiency, we present an approach to obtain controlled chromaticity and stability over short and long term from a set of initially optimized settings. A new color control system is described and implemented for a five–color LED light engine, covering a wide white gamut. The system provides intelligent control of the individual LED color arrays to produce high quality white light ranging in CCT between 3000 K and 6000 K. A feed-back control system combines a new way of using pre-calibrated lookup tables and a rule-based optimization of D_{uv} from the Planckian locus for each CCT with a calibrated color sensor for chromaticity control.

A pre-calibrated lookup table is generated using a new algorithm, called Ideal White Light Radiator-guided search algorithm (IWLiR), which can provide spectral mixtures characterized by a high general color rendering index (CRI) of $R_a > 85$ and a specific CRI $R_9 > 40$ for rendering the strong red objects e.g. skin tones. The Monte Carlo simulation process analyses the color variations (such as CCT and D_{uv}) and Φ_V based on the uncertainties in the input parameters for the light engine. These uncertainties are experimentally measured values multiplied by a factor of 20 to judge the functionality of the color control system. Introducing the perturbation on the system uncertainties enables the lamp to lamp calibration. A color sensor has been implemented to get feedback from the light output in real time to control these CCT and Φ_V variations. The calibrated color sensor monitors the chromaticity of the mixed light and also provides the correction factor for the current driver so that a new lookup point can provide the desired light output. The long term stability and accuracy of the system has been investigated with a target tolerance within a circle radius of 0.0013 (CIE TN001:2014) in the uniform chromaticity diagram (*CIE 1976*). The present control system shows the limitation in controlling D_{uv}. The future work will control the third dimension of the color control by using the tristimulus values of the color sensor. Presently, the uncertainty contributions due to faulty LEDs and LED ageing have not been taken into consideration. Future work will also include these contributions. Finally, the control system will be experimentally validated.

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