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Beczkowski, Szymon; Munk-Nielsen, Stig

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Szymon Bęczkowski, Stig Munk-Nielsen
Department of Energy Technology, Aalborg University
Pontoppidanstræde 101, 9220 Aalborg Ø
sbe@et.aau.dk, smn@et.aau.dk

Abstract-**Amplitude modulation is rarely used for dimming light-emitting diodes in polychromatic luminaires due to big color shifts caused by varying magnitude of LED driving current and nonlinear relationship between intensity of a diode and driving current. Current-voltage empirical model of light-emitting diode devices, presented in this paper, creates a way to estimate diode's colorimetric properties based on driving current and diode's voltage. The accuracy of the model was tested under direct and pulsed driving current. For DC current, the color difference between the modeled color point of the diode and the actual measured one, is much lower than the just noticeable color difference (mean ΔE_{ab}* < 0.15). The model can be used e.g. as a color feedback mechanism in high power trichromatic luminaires such as profile lamps.**

I. INTRODUCTION

Conventional light sources, like incandescent and halogen lamps, using heated metal filaments to generate light, or fluorescent lamps, that use electrically excited mercury gas and phosphor to down-convert the ultraviolet radiation into visible light, are gradually being replaced by light-emitting diodes. The invention of LEDs is more than a century old, but until now, LEDs did not have enough power to successfully replace conventional light sources. Recent advances in high power LED devices, with the availability of high efficacy: red, green, blue and white diodes, allows this devices to reach general lighting market.

Light-emitting diodes have many advantages over traditional light sources. They have a small footprint, the packaging does not contain glass components making the device robust and the lifetime of the device is estimated to exceed 50000 hours in some conditions. Their light output gradually decreases during the normal device operation towards the end of LED life whereas the conventional light sources tend to fail catastrophically at the end of their life. Moreover, their low voltage operation gives many control opportunities so that the light intensity can be controlled flicker free in the full intensity range.

LEDs generate light by means of electroluminescence. It occurs when free electron and hole recombine in the LED semiconductor structure. This pair of free carriers generates one photon whose wavelength is dependent on the band structure of the LED active area. Using semiconductor materials with different bandgap the wavelengths generated by a LED structure can be controlled. High power red LEDs are typically made using an AlGaInP semiconductor. Blue and green diodes use InGaN structures. Generally, light-emitting diodes generate a narrow spectrum with the full width at half maximum in the range of 20-30nm depending on the diode color yielding a saturated light color.

High intensity white LEDs are created by placing a thin layer of phosphor material on a blue LED chip so that a part of blue light is down-converted to yellow light and then by principles of additive color mixing the output light is perceived as white.

Light-emitting diode based light sources are used in various applications ranging from LCD screen backlighting, mood lighting, general illumination, street lighting, architectural lighting and profile lamps. Depending on the particular application, various LED composition and installed power are needed. Street lighting requires generation of white light with high efficacy and low color quality thus the luminaire may consist only of phosphor converted white diodes. Mood lighting and profile lamps are designed to generate colored light at various intensity levels. These luminaires are typically made using plurality of saturated color LEDs.

Polychromatic LED based light sources usually consist of at least red, green and blue diodes. This combination of devices yields wide luminaire gamut while maintaining high efficacy during white light generation. In order to generate desired light intensity and chromaticity, the brightness of individual LEDs in the luminaire has to be adjusted.

Properties of LEDs are strongly dependent on their driving current and junction temperature. The junction temperature is changing during normal lamp operation due to self heating and ambient temperature change. Both color point and luminous intensity of diodes change as a function of junction temperature and driving current magnitude [1]. Because of this phenomenon the driving current of each LED needs to be actively adjusted to reflect the changes in LED parameters in order to keep the desired output color constant.

Various color control schemes can be designed to keep the color point of a luminaire stable. Regardless of the control method, the output light is best kept below the just noticeable color difference level so that multiple luminaires with the same color command appear to generate identical color. The difference between two colors is measured as an Euclidean distance on a $L^*a^*b^*$ color plane and $\Delta E_{ab}^* = 2.15$ is assumed to be the just noticeable difference [2].

Except from the trivial open loop control (Fig. 1a), two different approaches can be seen in the literature for designing a color control scheme [3]. One employs a color sensor to feed back the colorimetric data (Fig. 1b). Another approach uses temperature, flux or other measurable quantity to estimate the tristimulus values based on predefined relationship (Fig. 1c). This approach utilizes LED models, of various complexity, that may include flux change with junction temperature and color point shifts with temperature and driving current (or duty cycle).
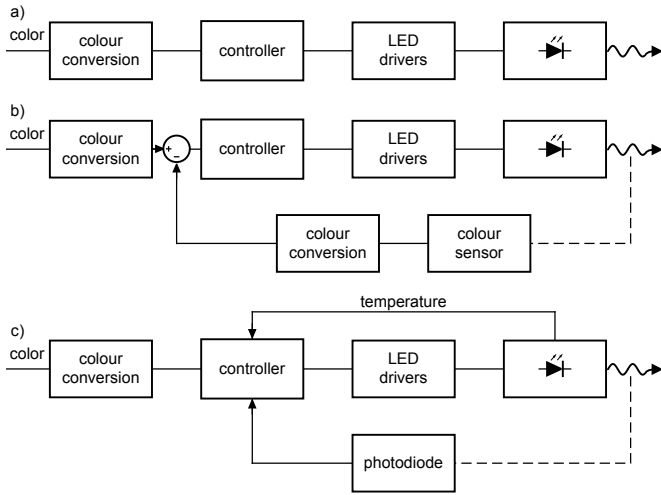
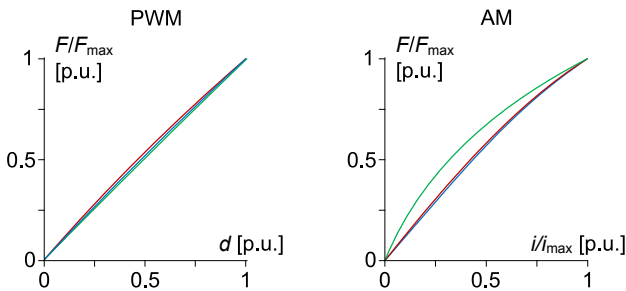Fig. 1. Color control methods: a) open loop, b) color sensor feedback, c) temperature and flux feedback.

Fig. 2. Dimming linearity for red, green and blue LED diodes under PWM and AM dimming shemes. PWM dimming shows almost ideal linear behaviour while AM dimmed diodes experience increased efficacy at low current level thus having a nonlinear flux-current relationship.
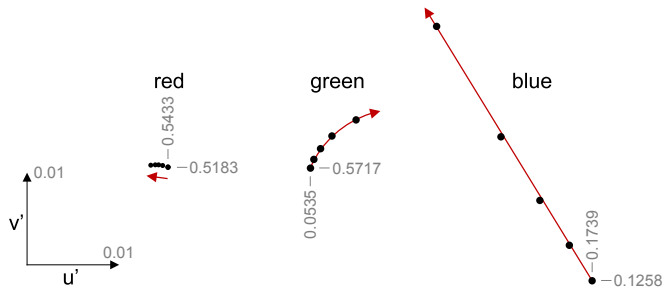

Fig. 3. Color point shift caused by AM dimming. Data points correspond to 1, 0.8, 0.6, 0.4 and 0.2 of nominal current. Arrows show the direction of lowering current.
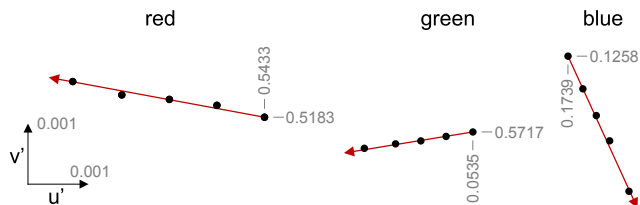

Fig. 4. Color point shift caused by PWM dmming. Data points correspond to 1, 0.8, 0.6, 0.4 and 0.2 duty cycle. Arrow shows the direction of lowering d. Note the scale change with respect to figure 3.

Color control loop in trichromatic RGB luminaires is typically done using three control loops, each controlling different diode color [3]. As red diode is the main contributor for the X tristimulus value color control loop for X controls the red diode. Similarly the Y and Z control loops controls the green and blue diode, respectively.

The intensity of individual LEDs is controlled by changing the average current supplied to the diode. Two driving techniques are commonly used in the industry: amplitude modulation (AM) where the magnitude of direct current is controlled and pulse width modulation (PWM) where diode is driven with pulsed current and intensity of the diode is controlled by the pulse duty cycle.

Due to filling of quantum wells and increase in parasitic Auger recombination the relationship between driving current and luminous flux of a diode is nonlinear (fig. 2). Furthermore, big color shifts occur while dimming LEDs with amplitude modulation (fig. 3) which may lower the accuracy of the color control loop.

Because of these drawbacks, PWM is often used to control the intensity of the diodes. PWM offers almost ideally linear control to output relationship for all diode types and colors (fig. 2) and yields much lower color point shifts during dimming (fig. 4) than amplitude modulation. Big color point shifts are caused by shift of spectrum towards shorter wavelengths for AlGaInP diodes and longer wavelengths for InGaN diodes [4].

Amplitude modulation can, however, bring additional efficacy benefits. The non-linear behaviour means increased efficacy at lower current densities. At some conditions using AM instead of PWM can increase the wall plug efficacy by a factor of two [1][5].

Current high power LED chips can be driven with current densities up to 2.5 A/mm² which yields currents up to 30 A in some LEDs [6]. Driving these high current devices with pulsed square-wave currents creates variety of problems including radiated EMI noise, and magnetostrictive and piezostrictive phenomena in passive components leading to increased losses and audible noise [7]. Therefore, it is beneficial to drive high current diodes with a DC current.

Due to the issues with driving high current LED devices with pulsed current, the direct current dimming seems as an attractive solution. Currently, however, there is no accurate feedback mechanism working well with AM dimmed luminaires. The main obstacle is the nonlinear dimming behaviour and big color shifts during dimming. Color control loop based on color sensor should, in theory, be able to compensate these effects but cheap trichromatic color sensors available on the market are very sensitive to spectrum shape change when working with narrow spectral sources like LEDs [8].

A current-voltage model, presented in this paper, creates a feedback mechanism that accurately predicts color shifts and intensity changes with both driving current change and temperature variations allowing the use of amplitude dimming in applications where color accuracy is important.
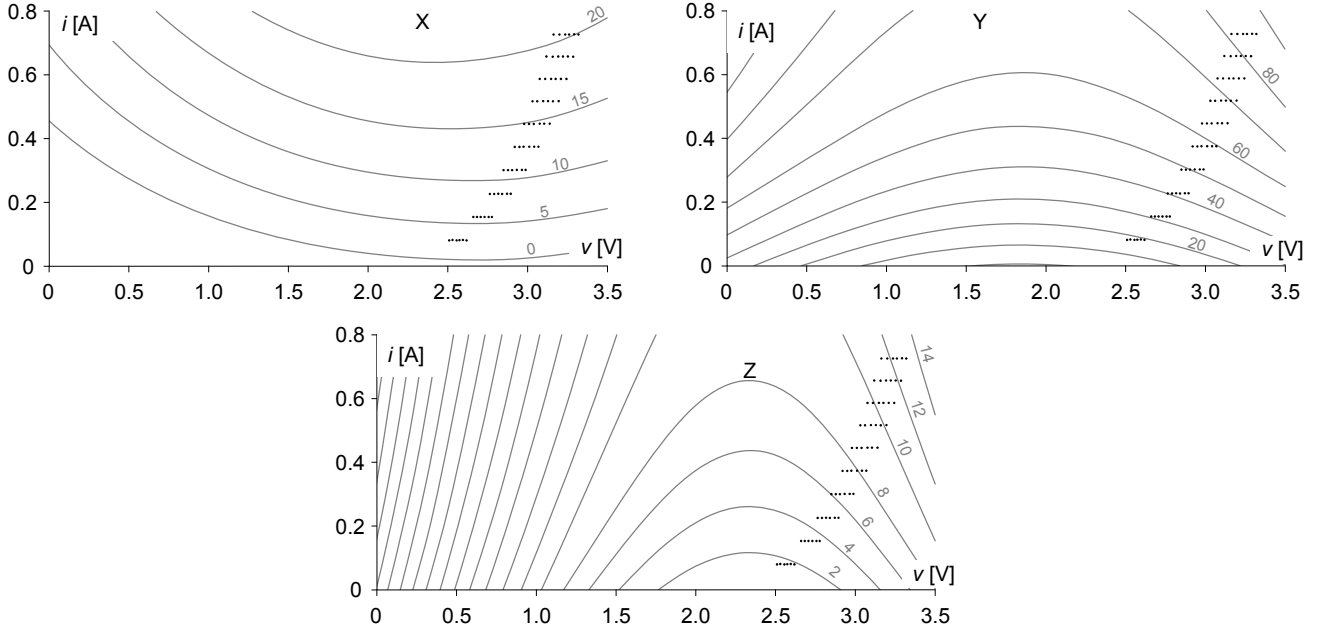
Fig. 5. Contour plots of the modelled tristimulus values on a current-voltage plane. Data points correspond to 5–105% of the nominal diode current and heatsink temperature in 5–55°C. Modelled X, *Y* and *Z* surfaces are only valid in the vincinity of the data points.

II. CURRENT-VOLTAGE MODEL

LED emission depends only on injected current magnitude and junction temperature. Various combinations of these two parameters yield different emission spectra and different conversion efficiencies. Since the model is used for color control, it is beneficial to measure the relationship between different combinations of current and junction temperature and *XYZ* tristimulus parameters.

It is, however, not possible to measure the diode's junction temperature directly, therefore many indirect measurement techniques have been presented in [9]. One of the methods uses the forward voltage temperature dependence. It is commonly used as temperature feedback mechanism in color control schemes [10][11]. Forward voltage of a diode is dependent on junction temperature and diode's forward current, therefore a single *iv* operating point corresponds to exactly one set of *i* and *T*j. This set of variable further corresponds to a single set of *XYZ* tristimulus values. Therefore a model of a diode can be built by measuring colorimetric and electric parameters at different operating conditions, namely driving current and junction temperature.

To create the model a green LED has been placed on a thermally controlled heatsink and mounted to the integrating sphere. The heatsink temperature was controlled in 5–55°C temperature range, every ten degrees. At each temperature level the current was controlled in 5–105% of the nominal forward current of the tested diode. After every change in either the heatsink temperature or the driving current the system was allowed to reach steady-state conditions at which point current, voltage and tristimulus values of the diode were recorded. In total the tristimulus values were recorded for 60 different operating points as seen in fig. 5. The number of these measurement points was chosen purely arbitrary, and it

may be possible to optimize the measurement procedure to include smaller number of points to increase the speed of device characterization. Furthermore, the self-heating of the diode can be used to vary the junction temperature instead of using the thermally controlled heatsink.

Measured data was fitted to three surfaces, describing the relationship between tristimulus values and electrical operating point. The relationship is nonlinear therefore a third order polynomial was used in following form:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} a_{0,X} \\ a_{0,Y} \\ a_{0,Z} \end{bmatrix} + \begin{bmatrix} a_{1,X} \\ a_{1,Y} \\ a_{1,Z} \end{bmatrix} i + \begin{bmatrix} a_{2,X} \\ a_{2,Y} \\ a_{2,Z} \end{bmatrix} i^2 + \begin{bmatrix} a_{3,X} \\ a_{3,Y} \\ a_{3,Z} \end{bmatrix} i^3 + \begin{bmatrix} a_{4,X} \\ a_{4,Y} \\ a_{4,Z} \end{bmatrix} v + \begin{bmatrix} a_{5,X} \\ a_{5,Y} \\ a_{5,Z} \end{bmatrix} v^2 \quad (1)$$

where a_n an are the polynomial coefficients. Values of the coefficients as well as goodness of fit for each function are summarized in table I.

The polynomial was chosen in a form of lowest order still representing well the measured data. It is possible to store the relationship between current, voltage and tristimulus values in other forms like look-up tables or splines depending on the desired precision and speed of algorithm.

To validate the model two tests were performed. The first test validated the accuracy of the current-voltage model when the diode was driven with DC current. Second test was performed with the diode dimmed with a PWM technique.

TABLE I
MODEL COEFFICIENTS FOR THE MEASURED DIODE

	a_0	a_1	a_2	a_3	a_4	a_5	R^2
X	−21.542	49.810	−38.892	16.166	17.368	−3.437	0.99997
Y	30.771	150.613	−119.993	45.017	−38.875	11.223	0.99991
Z	33.134	14.216	−6.900	2.056	−28.765	6.248	0.99986

		measured			modelled			
v [V]	i [V]	X	Y	Z	X	Y	Z	$\Delta E_{ab}{}^{*}$
3.1388	0.5253	16.9172	71.9150	10.2662	16.8831	71.8476	10.2611	0.0049
2.9731	0.3523	13.1429	54.6397	7.0978	13.1382	54.5288	7.0802	0.0661
3.0566	0.4648	15.8201	65.5589	8.9330	15.8011	65.3945	8.9049	0.0738
3.1348	0.6151	18.8465	76.8877	10.9423	18.8098	76.9110	10.9700	0.0596
3.1809	0.6949	20.2167	82.2945	12.0135	20.1803	82.4884	12.0872	0.3098
2.8123	0.2355	9.9357	39.5305	4.6286	9.8996	39.6049	4.6435	0.2676

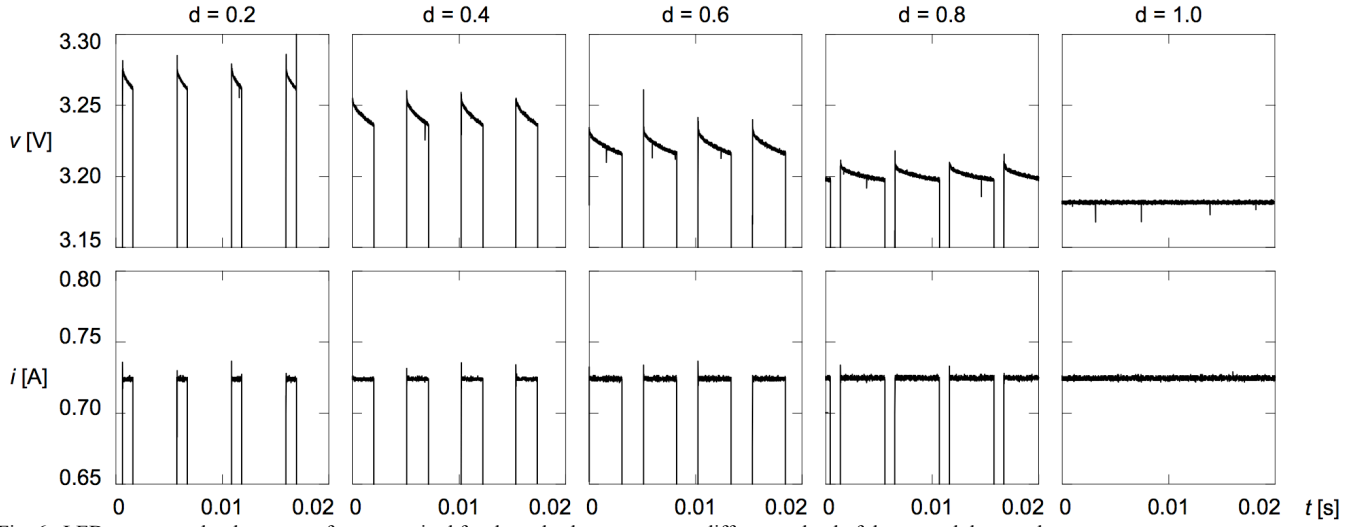|	measured			modelled			
d	X	Y	Z	X	Y	Z	$\Delta E_{ab}{}^{*}$
0.2	4.0447	17.3423	2.6773	3.8695	16.6655	2.5735	2.4091
0.4	8.1630	34.4009	5.2286	8.1669	34.6032	5.2597	0.4614
0.6	12.5078	51.9626	7.8009	12.5364	52.2906	7.8480	0.4869
0.8	16.8984	69.2601	10.2805	16.9262	69.5062	10.3069	0.1671
1.0	20.7419	83.9519	12.3199	20.7569	84.0777	12.3363	0.0319

Fig. 6. LED current and voltage waveforms acquired for the pulsed current test at different valued of the control duty cycle.
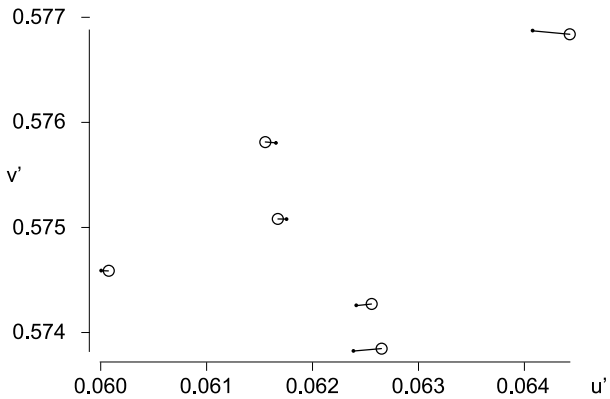

Fig. 7. Measured (o) and modelled (·) color points for six different operating points (random driving current and heatsink temperature) shown on CIE1976 $u'v'$ diagram. Data points correspond to the data shown in the table II.

A. Model verification at direct current

In order to test the model under DC current, six measurement points were collected at random heatsink temperatures and diode current levels. Measured electrical quantities were used to estimate tristimulus values using the diode model and then compared to the measured tristimulus values. Results are summarized in Table II. The color distance between the measured and the modeled values is always below the just noticeable distance value. Fig. 7 shows the actual and measured color points on a CIE1976 $u'v'$ color chromaticity diagram.

B. Model verification at pulsed current

Similar verification was performed under pulsed current waveforms. The diode was driven with 200Hz PWM pulsed current with different values of duty cycle d. The temperature of the heatsink was kept constant and after each change in duty cycle the system was allowed to reach thermal steady state. Current and voltage waveforms were recorded with 125kS/s sampling over several current pulses (fig. 6). Simultaneously, colorimetric properties were measured with integration time much higher than single PWM period.

A portion of the measured signal was discarded so that the data would contain only a number of full PWM cycles. This ensures that the average value of the sampled waveforms would correspond to the average value per single pulse and therefore the whole signal.

Current and voltage signals were then converted into tristimulus data using previously described LED model. Resulting vectors of colorimetric data were integrated and the resulting values divided over measurement period to get average values. Table III compares the measured and modeled tristimulus values and shows the color distance between the corresponding color points.
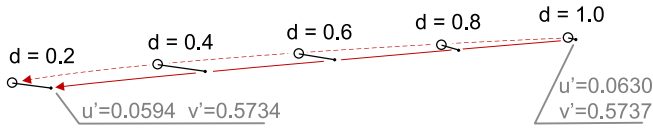

Fig. 8. Difference between measured color point shift for PWM dimming (dashed line) and color shift obtained using current-voltage model (solid line). Arrows show the direction of decreasing flux.

Measured color points and corresponding color points estimated using diode model are shown in fig. 8. The model accurately predicts the direction and magnitude of the color shift caused by the PWM dimming. The accuracy of the method lowers with lowering duty cycle. This may be attributed to fast thermal transients at the beginning of the pulse that are not measured accurately. In low duty cycle conditions this transient starts dominating voltage waveform. Shorter pulse contains low number of samples therefore noise may influence the measurement and therefore the accuracy of the model drops.

Presented results show that the current-voltage model accurately predicts colorimetric properties of light-emitting diodes, especially when driven with direct current.

III. COLOR CONTROL

The aim of this model is to create an accurate color feedback for AM dimmed luminaires. This chapter gives a brief description of the color control loop that can be implemented using the aforementioned model.

Basic color control loop created using the diode model, shown in fig. 9, compares the actual tristimulus values with the command values. Each diode color has a separate model. Measured electrical quantities are used to estimate the instantaneous colorimetric properties. The respective tristimulus values of each diode color are added to calculate the tristimulus values of the mixed light. These values are compared with the color command to produce the error vector. The error is then forwarded to a controller (e.g. PI) to create a necessary compensation in diodes' driving currents.
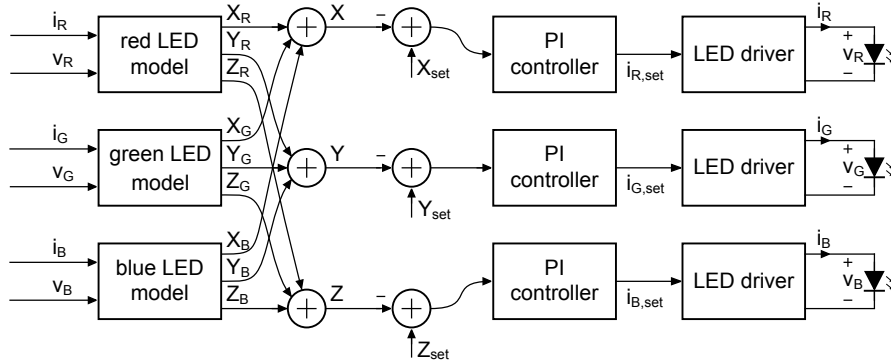

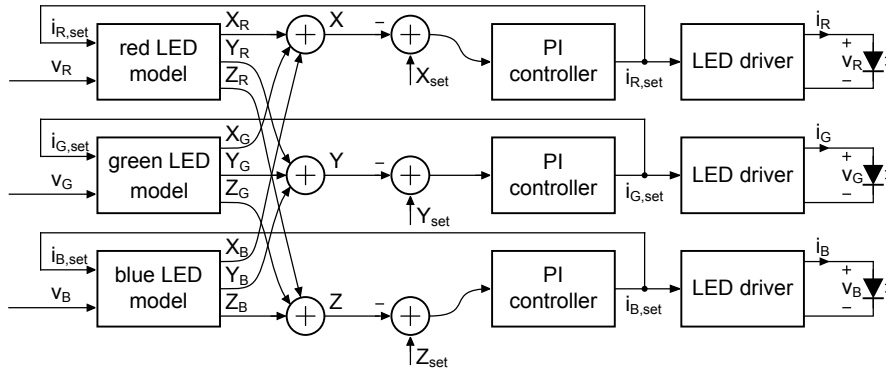Fig. 9. Color control loop utilizing three current-voltage models.

Fig. 10. Modified color control loop utilizing three current-voltage models. Because the drivers' current control loop is much faster than the color control loop the current cmmand value can be treated as equal to the actual LED current and used as a feedback variable.

Human eye cannot see light fluctuations above 60 Hz in foveal vision [12]. The bandwidth of the color controller can be limited to this value. If fast changes in light intensity are not necessary the bandwidth can be further reduced to limit the necessary processing power of the luminaire's microcontroller. Load changes are dependent on LED thermal cooling path properties. The active area and the LED structure heats up in the millisecond range, but this change is too fast for the human eye to see so this transient does not need to be controlled. The diode will change its properties when the heatsink changes its temperature. The time constant of a heatsink can be in range of tens of seconds to few minutes so the parameters change with heatsink temperature is easily compensated.

As the current information is present in the color control loop in the form of current command and the rate of the load change is low, the current control signal can be fed into LED models to eliminate the need for three current sensors (fig. 10). As long as current control loop of LED drivers is much faster than color control loop, both control loops can be decoupled and the relationship

$$i_{n,set} = i_n \qquad (2)$$

is valid for the purpose of estimating the tristimulus values. This reduces the number of sensors needed in the control system. Each diode color requires only a single voltage measurement.

IV.   CONCLUSIONS

Diode behavior under AM dimming was presented. It is shown that the relationship between luminous flux and driving current is nonlinear and dependent on the diode type. Also the color point shift was shown to be a magnitude higher than under PWM dimming.

A simple, empirical model of light-emitting diode device was presented. The model uses information about diode's current and voltage to estimate colorimetric properties of the diode. Relationship between electrical and colorimetric quantities requires a nonlinear model. A third order polynomial was used to demonstrate the model, but any other representation, like look-up tables, can be used.

The accuracy of the model was measured under both DC and pulsed current, these being the most common dimming mechanisms. In both cases the model predicts the colorimetric properties accurately, but in the pulsed current case requires much higher computational power to utilize the model than in AM dimmed case.

The model can be used as an accurate feedback mechanism in AM dimmed luminaire. The current measurement signal can be replaced by the current command value to decrease the number of sensors used. In this case only a single voltage measurement per color channel is needed.

Presented model is valid for a single light-emitting diode of any colour. Typically, in luminaires, diodes are used in strings to increase the total light intensity. Although it is possible to measure the voltages of each diode in the string and create a current-voltahe model for each of these diodes, such a system would not be practical.

It is possible to create a single model for all diodes connected in string treating these diodes as a single device, however the resulting accuracy has not been measured yet and is a part of future research interest.

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