LED application specific calibration method for color measurements

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***Abstract*—More and more light applications use multiple light emitting diodes to generate defined light spectra. Often reaching defined brightness levels and an exact color coordinate or color temperature is desired. The LEDs change their light spectra over time or under influence of different environmental temperatures. One possibility is to compensate the resulting color shift of the illumination by integrating a color sensor. Before the light can be re-adjusted or regulated, a precise color measurement must be guaranteed. This paper studies the color measurement accuracy, based on specific filter curves of sensors and models of red, green, blue and white LEDs fitted to measure data.**

I. INTRODUCTION

The spectrum of light emitting diodes (LEDs) change depending on the ambient temperature, the utilized current or the age. Even spectral changes due to pulse width modulation (PWM) can be detected. When marketing LED illuminations, the question about long-term availability of the LEDs or similar future batches arise. In [7] four solution approaches to compensate the problems of LEDs are addressed. A promising solution is direct feedback control by using the tristimulus values of the emitting light source. One presented idea is to use a color sensor to measure the LED light color and regulate it actively via LED control features. This concept is for example mentioned in [1], [6] and [5]. The accuracy of the feedback control system is significantly influenced by the measurement accuracy of the sensor. Thus, one important part is the sensor calibration. [2] demonstrates a calibration method for a RGB sensor along the black-body curve.

In this paper the measurement accuracy over the complete LED system-specific color space is considered. The authors of this paper decided to develop a simulation environment to compare multiple sensors using an RGB and RGBW LED system. First we measured the spectral sensitivities of the chosen color sensors. The second step was the generation and fitting of a model of the red, green, blue and white light emitting diodes. The following measurement simulation is based on the selected sensor filter curves and a theoretical model of the LEDs.

II. COLOR SENSORS

Two different types of color sensors are considered in this paper. Both sensors have three characteristic curves. The first sensor is a typical RGB sensor with the highest sensitivity of the channels and peak values at 454, 560 and 660 nm [3]. The sensor has an integrated infrared blocking filter to prevent measurement errors caused by infrared light. The second sensor type is called True Color Sensor [4] and the characteristic curves correspond to the 2° standard observer. Due to tolerance in manufacturing process, it is not possible to produce filter curves without any deviation. Fig. 1 shows the remaining differences in spectral sensitivity between the standard observer and the sensor. Because of this it is also necessary to calibrate the True Color Sensor. For the determination of the influence of the manufacturing tolerances the spectral sensitivities were measured for 10 RGB and 10 True Color Sensors.

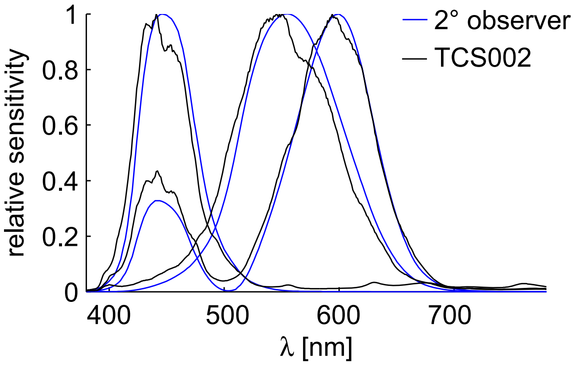

Fig. 1. Characteristic curves of 2° standard observer and True Color Sensor.

III. LED MODELLING

The developed LED models serve as a basis for the color measurement simulations. The goal of this development was to find a function for each LED, because the LED datasheets includes no information about the spectral shift depending on the current or PWM. With the indication of the PWM, current and the ambient temperature the function should calculate the LED spectrum. We decided to build a test setup and measure the RGBW light emitting diodes. In future it will be possible to compare the simulated results with the actual results.

A. Experimental Setup

On the one hand the experimental setup, shown in Fig. 2, allows the measurement of the LEDs. On the other hand the test setup contains a color sensor to validate the theoretical results in a future study. The ambient temperature of the LEDs can be adjusted between 30 and 80°C. The LED currents can be increased stepwise up to 700 mA. Furthermore the LEDs can be dimmed by using a 12 bit PWM signal.

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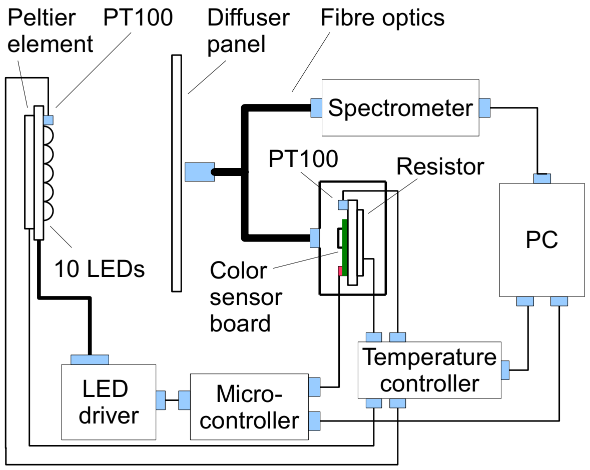

Fig. 2. Experimental setup.

B. LED Modelling

The model of each LED is based on 756 spectra, measured with the spectrometer. Using the presented test setup the light emitting diodes were considered at six temperature levels between 30 and 80 degrees Celsius. At each temperature level the LEDs were measured with different PWMs between 0 and 100% at an interval size of 5% at several current levels. At the end of each measurement process we receive a quadruple consisting of temperature, current step, PWM step and the associated value for each wavelength. So it is possible to determine a function $f(temperature, current, PWM)$ for a specific wavelength. 756 quadruples were used to determine the coefficients for the chosen linear interpolation. The subsequent validation showed almost no differences between the input spectra and the generated spectra. Figure 3 shows several simulated spectra of the four used LEDs. The black lines in the figure show measured spectra taken by a spectrometer. The blue spectra between the corresponding two black spectra are calculated by the interpolation function f. The following simulation of color measurement used the LED model with a constant temperature and current. Thus the remaining cause of the spectral shift is the influence of the pulse-width modulation. The resulting color deviation differs between the LEDs. The red LED has the highest color shift of 0.0016Δu'v' compared to 0.0015Δu'v' for the blue LED, 0.0008Δu'v' for the green LED , and 0.0006Δu'v' for the white LED.

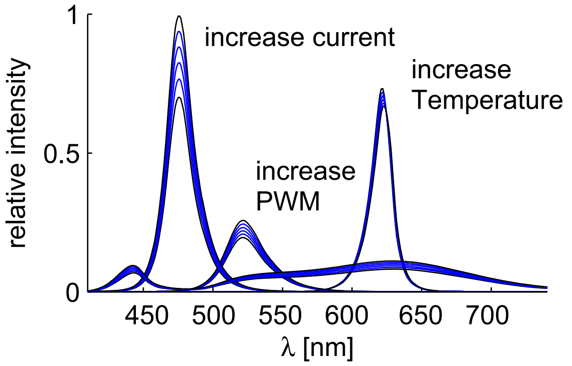

Fig. 3. Spectra interpolation [blue spectra] between two measured led spectra [black spectra].

IV. COLOR MEASUREMENT SIMULATION

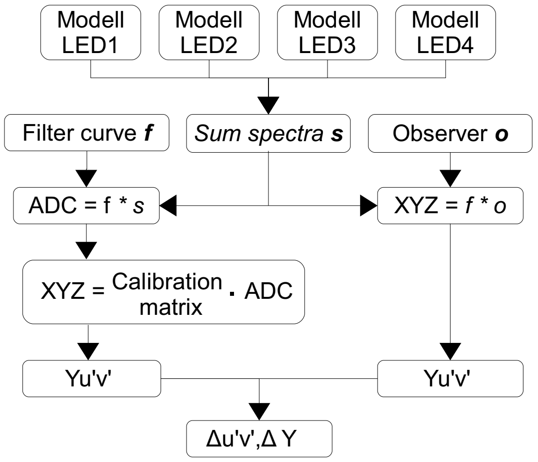

Fig. 4. Workflow of the simulation process.

Figure 4 shows the workflow to simulate the measurement process and compare the result with the observer as reference. In the first step the illumination spectrum is calculated by combining the LED models. It is possible to set the current level, the PWM and the temperature for each LED. The resulting spectrum is the input to calculate the tristimulus values XYZ via the standard observer. On the other hand the convolution between the illumination spectrum and the sensor characteristics result in the simulated sensor response values. It is necessary to multiply the result vector with the calibration matrix M to receive the XYZ values (shown in equation 1).

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} m_{1,1} & m_{1,2} & m_{1,2} \\ m_{2,1} & m_{2,2} & m_{2,2} \\ m_{3,1} & m_{3,2} & m_{3,2} \end{pmatrix} * \begin{pmatrix} Ch1 \\ Ch2 \\ Ch3 \end{pmatrix} \tag{1}$$

$$u' = \frac{4X}{X + 15Y + 3Z} \tag{2}$$

$$v' = \frac{9X}{X + 15Y + 3Z} \tag{3}$$

$$\Delta u'v' = \sqrt{(u'_2 - u'_1) + (v'_2 - v'_1)} \tag{4}$$

Because of the perceptual uniformity the CIELUV color space is recommended to measure color deviation. In the last step both results are converted to the color space (Eq. 2 and 3) and the color as well as brightness deviation is calculated (Eq. 4).

$$M = (A_{XYZ} * A'_{sensor}) * (A_{sensor} * A'_{sensor})^{-1} \tag{5}$$

First we use the standard calibration with pseudo-inverse (see equation 5). This calibration method is possible for RGB and True Color Sensor, however it is required to calibrate each sensor individually. At the beginning the calibration matrix is calculated within a calibration process. The matrix A_{sensor} consist of the sensor values for each LED at full PWM. A_{XYZ} includes the corresponding reference values XYZ of the LEDs under a 2° standard observer. Both matrices have the same size, for example 3x3 with a RGB or 3x4 with a RGBW LED system.

A. RGB LED System

To compare the measurement accuracy between the RGB sensor and the True Color Sensor it is necessary to review several LED input combinations. For the RGB LED system we chose all combinations of the three LEDs from 0 to 100% PWM with a 12.5% interval size. Figure 5 shows the color measurement deviation for one of the RGB and True Color Sensor at the resulting 728 target points. The average deviation of the RGB sensor Δu'v' 0.0017 is 11 times higher than Δu'v' $1.55 \cdot 10^{-4}$ for the True Color Sensor. The boxplot Fig. 6 shows the accuracy for all twenty color sensors. Both color sensors have the same behavior, but the True Color Sensor is much more accurate. All sensors measured the brightness better than +/- 0.5% ΔY. The worst case is a LED combination where only the red LED is used and dimmed via PWM. This is due to the fact that the red LED has the highest color shift over the PWM. The simulation shows that the small LED color shifts due to the PWM decrease the sensor accuracy. It is possible to increase the accuracy by extending the calibration. For example the measurement accuracy can be doubled via additional calibration sets for each LED at several PWM stages. Furthermore, the color deviation between the ten color sensors of one type differ greatly. The quality of the sensors spectral sensitivity are the reason for these differences. Using specific filter curves with only little deviation to the standard observer reached a Δu'v' smaller than 0.001 (data not shown). During the actual simulation the LED ambient temperatures was constant. However, if a small spectral shift over the PWM results in a color deviation - it is also necessary to review the influence of the LED shift during temperature changes. Usually, the calibration matrix is calculated at 30°C ambient temperature of the LEDs. Subsequently, we increased the LED temperature and simulated the color measurements for all LED input combinations. In this scenario we ignored the temperature influence of the sensor. Fig. 7 shows the influence of the ambient temperature. The result is that the measurement deviation increases with the temperature. That means that the accuracy is worse the higher the spectral shift is between the calibration spectra and spectra of the LEDs at the operating temperature.

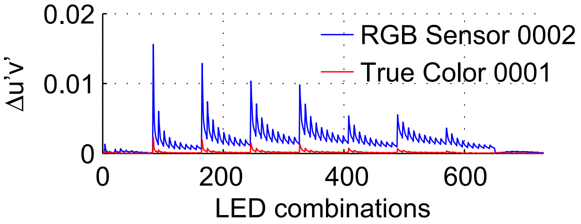

Fig. 5. Color deviation for True Color and RGB sensor. Each measurement series include 728 target points (RGB LED System).

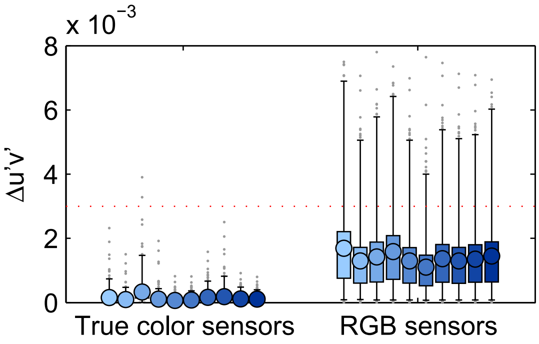

Fig. 6. Comparison of the measurement accuracy between both sensor types. Each box include one measurement series about 728 led configuration (RGB LED System).

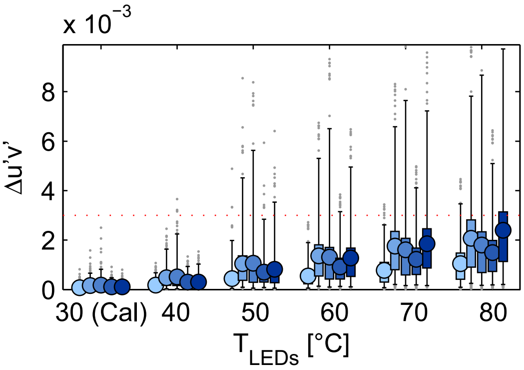

Fig. 7. Change of the measurement deviation by increasing the ambient temperature of the RGB LED system. The True Color Sensor was calibrated at 30°C ambient temperature of the LED.

B. RGBW LED System

For the measurement simulation with the RGBW LED system we chose all combinations of the LEDs from 0 to 100% PWM with 25% interval size. First we simulated the measurement process with the same calibration method as used in the RGB system. But the results showed that the simple way to extend the calibration with an additional data set for the white LED is not accurate enough. For example the best True Color Sensor has a average deviation of 0.003Δu'v' and in the worst case of 0.0182Δu'v'. Furthermore the sensor shows a strong brightness deviation (+/- 4% ΔY). One solution is to increase the number of data sets during the calibration process. On the one hand it is necessary to find the right combination of data sets and on the other hand it is important to use minimal effort. In [8] a optimization program is used to find the optimum between the number of input data and accuracy. This approach requires many initial measurements.

In this paper we looked for a solution without least calibration effort. An other way to get better results is to integrate further information about the actual LED control sets. If the sensor logic has information about

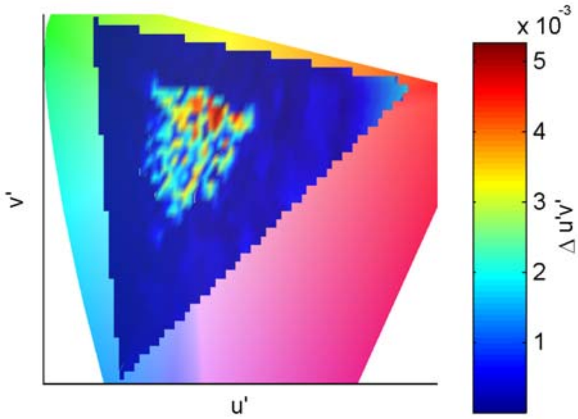

Fig. 8. Distribution of the color measurement deviation of a True Color Sensor and a RGBW LED system by using the PWM calibration.

the actual PWM of the LEDs it is possible to calculate a customized correction matrix for each measurement process during the LED operation. At the beginning in the calibration phase it is only necessary to measure the four data sets (for each LED). For each measurement during the LED operation the correction matrix will be calculated with (6) and (7) as calibration input. In which the vector $\overrightarrow{p}$ corresponds to the actual PWM of the LEDs.

$$A_{XYZ} = \begin{Bmatrix} p_r X_r & p_g X_g & p_b X_b & p_w X_w \\ p_r X_r & p_g Y_g & p_b Y_b & p_w Y_w \\ p_r Z_r & p_g Z_g & p_b Z_b & p_w Z_w \end{Bmatrix} \tag{6}$$

$$A_{Sen} = \begin{Bmatrix} p_r C1_r & p_g C1_g & p_b C1_b & p_w C1_w \\ p_r C2_r & p_g C2_g & p_b C2_b & p_w C2_w \\ p_r C3_r & p_g C3_g & p_b C3_b & p_w C3_w \end{Bmatrix} \tag{7}$$

Fig. 8 shows the measurement deviation of one True Color Sensor at the 624 test color point. The integration of the PWM factor improves the measurement results, for example the average deviation decreases from 0.003 to 0.0009 Δu'v'. But it is obvious, that the calibration has problems with LED combinations where all four LEDs are powered with different PWM levels. For example the worst case in the simulation is the RGBW combination of [0.75 0.5 0.25 1].

First calculations showed that the results were better if the calibration matrix is calculated with additional data sets near the actual LED combinations. It is neither useful to integrate data sets all over the color space nor all possible LED combinations. But it is possible to set a focus with a theoretical data set. Due to the additive color mixing, we can calculate $\overrightarrow{XYZ_{calc}}$ with the actual PWM setting and the initial calibration data sets at full PWM (Eq. 8). The associated $\overrightarrow{Ch_{calc}}$ can also be calculated with the actual PWM control and the sensor response of the calibration data at full PWM.

$$\begin{pmatrix} X_{calc} \\ Y_{calc} \\ Z_{calc} \end{pmatrix} = \begin{pmatrix} p_r X_r + p_g X_g + p_b X_b + p_w X_w \\ p_r X_r + p_g Y_g + p_b Y_b + p_w Y_w \\ p_r Z_r + p_g Z_g + p_b Z_b + p_w Z_w \end{pmatrix} \tag{8}$$

The calculated data set is integrated as a fifth data set (additional to the four LED data sets) during the calculation of the calibration matrix (Eq. (5)). Therefore, it is required to calculate the calibration matrix for each measurement process. Figure 9 evaluates the three calibration methods. With the extended calibration method (CT) all True Color Sensors had a color measurement deviation of $\leq$ 0.002Δu'v'. The brightness can be measured at deviation levels better than +/- 0.5% Y. The comparison between the two sensor types shows that for an RGBW LED system the usage of an RGB sensor is inferior. The measurement accuracy of the RGB sensor is greater than 0.0121 Δu'v' and +/-3.1% ΔY (data not shown). The first measurements with the test system confirmed the simulation. In future studies we would also include the temperature dependence of the chosen sensor.

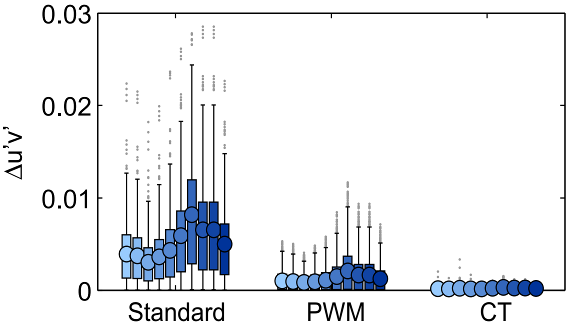

Fig. 9. Color measurement deviation for 10 True Color Sensors depending on the chosen calibration method. Each box include one measurement series about xxx led configuration using a RGBW LED System.

V. CONCLUSIONS

This paper shows a simulation of different calibration methods for LED light measurements via color sensors. The simulation is based on the sensor characteristics and several experimentally fitted LED models. Using the models it is possible to generate the LEDs spectrum depending on current, PWM and temperature. In both selected applications, RGB and RGBW LED systems, the True Color Sensor achieves better results than the RGB sensor. The calibration matrix calculated with the standard method can be used to measure an RGB light source with sufficient accuracy. To measure the light of a RGBW LED system it is useful to extend the calibration process with additional calculated data sets. The extended calibration sets can be calculated at each measurement cycle. Thus, the initial calibration process is unaltered. The results show that in the simulation the True Color Sensor reached a maximum Δu'v' of 0.002 and a brightness deviation of +/-0.5% ΔY. The calibration method also improves the result of the RGB sensor. These results however are still inferior to the accuracy of a True Color Sensor within an RGBW system.

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