

Control of LEDs

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Abstract— There is a strong interest in using LEDs for general illumination due to the potential they offer for energy saving, environmental friendliness, new opportunities in lighting design, and control of the intensity, color, and spatial distribution of light. General illumination requires primarily white light that can be obtained by mixing e.g. the light of red, green, and blue LEDs. This enables also color adjustability, which is considered to be a most attractive feature of future LED lamps. There is common consent that when using color mixing some kind of feedback control must be applied in order to meet color accuracy requirements. In this paper color control concepts are briefly reviewed and control of a lamp with more than 4 primary LED colors is reduced to the known control of 3 primary LED colors. Measurements are provided for the temperature dependence of LED and color sensor characteristics. Color control implementation is outlined using a laboratory setup based on a rapid color control prototyping system which uses commercially available software and digital hardware amended by custom in-house developed hardware. The rapid control prototyping system is applied to control the color of an experimental RGB LED lamp.

Keywords— light-emitting diodes; color control; multiple primaries; LED characteristics; sensor characteristics; rapid control prototyping

I. INTRODUCTION

Light-emitting diodes (LEDs) are nowadays widely used in special lighting areas like e.g. traffic lights, signaling, signage, and outstanding architectural implementations. However, these are niche applications compared with general illumination. There is a strong interest in using LEDs for general illumination due to the potential they offer for energy saving, environmental friendliness, new opportunities in lighting design, and control of the intensity, color, and spatial distribution of light. Next to improving the LEDs' efficiency and reducing their cost, improved thermal management and color control are considered to be the key challenges lying ahead [1].

LEDs are light sources with narrow spectra that are typically a few ten nanometers wide. As a consequence of this they emit light with saturated colors and their color points are located close to the perimeter of the chromaticity diagram (Fig. 1) [2].

General illumination requires primarily white light located in the center of the chromaticity diagram. There are two basic alternative solutions for making white light using LEDs, either color mixing or using phosphors for down converting the light

of ultraviolet or blue LEDs [1]. Whilst down conversion can be implemented in a more straightforward way, color mixing enables color adjustability, which is considered to be a most attractive feature of future LED lamps. Mixing e.g. the light of red, green, and blue LEDs, any color can be created inside the triangle defined by the LEDs' chromaticity coordinates (Fig. 1). However, color reproducibility and stability issues remain to be solved for both alternatives. Lamps with nominally identical color points will have to be operated next to each other without noticeable color differences. Replacing one of these lamps, even after some years, also must not result in noticeable color differences.

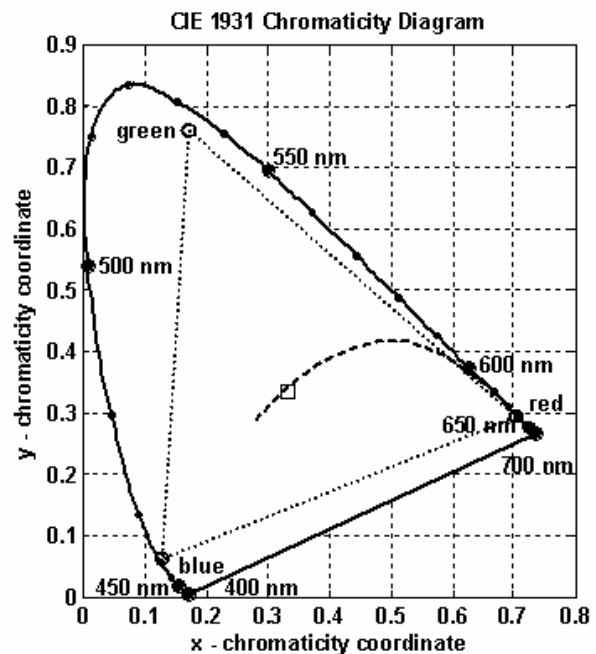


Figure 1. Empty circles: Typical Lumileds Luxeon I red, green, and blue LEDs [3]. Dotted triangle: Color gamut resulting from mixing the light of these LEDs. Dashed line: Location of blackbody radiators. Empty square: Equal-excitation locus ($x=1/3$; $y=1/3$) white [2].

Maintaining the color of a LED light source within acceptable tolerances is difficult since their optical properties vary with manufacturing spread, aging, temperature variations, and drive current amplitude variations [4]. There is common consent that when using color mixing some kind of feedback control (Fig. 2) must be applied in order to meet the color

accuracy requirements [4-10]. Calibrating the LED light source commonly compensates for manufacturing spread. Aging affects mainly the brightness of LEDs whilst their color points can be assumed to be stable over time. Usually, these brightness variations are accounted for using a flux or a color sensor. Calibrating individual LED light sources at different temperatures is cumbersome. It can be avoided if sufficiently accurate temperature dependent models of the optical characteristics of the LEDs are available. The impact of drive current amplitude variations is usually suppressed by keeping it constant and using pulse width modulation for dimming the primary LED colors.

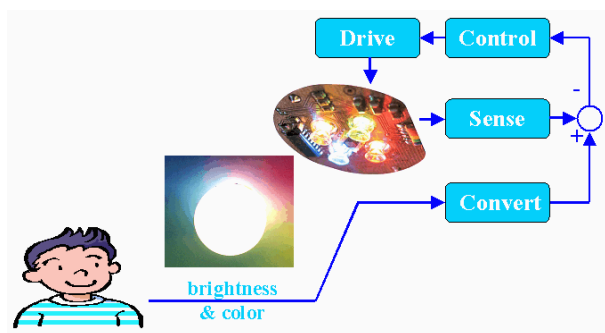


Figure 2. LED lamp feedback color control system. User requirements (brightness, color) are converted into electrical quantities (voltages, currents) towards which the system (sense / control / drive / LEDs) is tuned. The user perceives the mixed light of the colored LEDs.

Different color control concepts have been proposed that are briefly reviewed in chapter II. These concepts have in common that calibration of LED lamps is combined with temperature, light, and color sensors integrated with the lamp in order to achieve color control. However, there is a vast range of possibilities from using only calibration and no sensors at all to using only highly accurate color sensors and no calibration at all. Ultimately, for all concepts the color accuracy achieved depends critically on the variation of the optical characteristics of the LEDs as a function of the junction temperature that is discussed in chapter III. Usage of sensors is frequently based on the tacit assumption that they do not suffer from the detrimental effects affecting the LEDs' optical characteristics such that a feed forward control based solely on calibration is not feasible. However, there are also e.g. limitations to the maximum operation temperature of light sensors that are discussed for color sensors in chapter IV. Ultimately, decisions on the color control concept have to be based on quantitative experimental evaluations. As an example for the color control implementation required for this purpose chromaticity coordinates feedback using a color sensor is described in chapter V. Use is made of a rapid control prototyping system (chapter VI) that is based on commercially available software and digital hardware amended by custom in-house developed hardware. The RCP system is applied to control the color of an experimental RGB LED lamp (chapter VII).

II. COLOR CONTROL CONCEPTS

Feedback color control of a LED lamp (Fig. 2) mixing the light of differently colored LEDs aims at adjusting their respective brightness such that light is created with the desired brightness and color, e.g. equal-excitation locus white (Fig. 1), assuming that the chromaticity coordinates of the LEDs are known. Previous work [4-10] concentrated on mixing the light of three different primary colors, usually red, green, and blue. However, mixing more than three different primary colors is desirable in order to obtain a lamp with good color rendering and high efficiency [11-13]. The task of controlling such a lamp can be reduced to controlling a lamp with three different primary colors, e.g. by introducing an auxiliary color P_0 and obtaining the light with the desired color P_x as the mixture of this auxiliary color and two primary colors (Fig. 3).

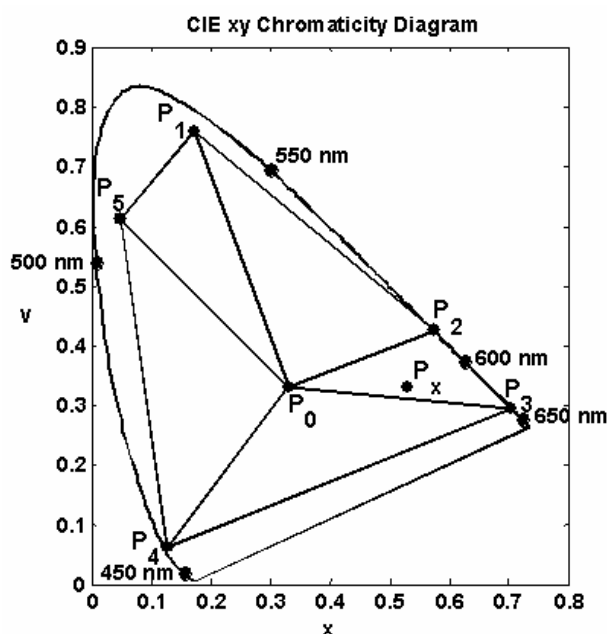


Figure 3. Reducing the task of controlling 5 primary colors (P_1 , P_2 , P_3 , P_4 , and P_5) to controlling 3 primary colors (P_2 , P_3 , and the auxiliary color P_0) in order to obtain mixed light with color point P_x .

Any target color point P_x can be realized by an appropriate choice of these two primary colors. If the contributions of the primary colors to the auxiliary color P_0 are chosen such that the latter is produced with good color rendering and high efficiency, then this will also hold for the other colors obtained using this control procedure.

As to the mixing of three primary colors, temperature feed forward, flux feedback, their combination, and chromaticity coordinates feedback have been suggested previously as color control concepts in [4] and partly validated in [4-9].

Applying neural networks to LED color control was suggested in [10] but without discussing its practical implementation. However, whilst the other color control concepts differ mainly as to the type of sensor and feedback signal used and specific driver requirements, neural networks

are primarily an independent concept for implementing the controller. Some general statements can be made as to the applicability of the different sensing concepts for LED color control:

A. Temperature Feed Forward

Temperature feed forward cannot account for the variation with aging of the luminous efficiency (luminous flux divided by electrical input power) of the colored LEDs. Therefore it is usually not considered to be applicable in practice.

B. Flux Feedback

Flux feedback cannot account for the variation with temperature of the chromaticity coordinates of the colored LEDs. Therefore it is usually not considered to be applicable in practice.

C. Temperature Feed Forward and Flux Feedback

Since temperature feed forward can account for the variation with temperature of the chromaticity coordinates of the colored LEDs and flux feedback can account for the variation with aging of their luminous efficiency, their combination is well suited for LED color control. This concept comprises specific timing requirements for coordinating driving and sensing, which exclude e.g. amplitude modulation of the LED currents.

D. Chromaticity Coordinates Feedback

This concept measures the chromaticity coordinates and the brightness of the mixed light emitted by the LED lamp directly. It is therefore well suited for LED color control. There are no specific driving requirements associated with this concept since the sensor signals are usually low pass filtered.

At present there is no clear preference for applying either temperature feed forward and flux feedback or chromaticity coordinates feedback. This choice will depend on application specific requirements and has to be based on a quantitative evaluation of the concepts.

III. LED CHARACTERISTICS

Whilst the impact of manufacturing spread on the optical characteristics of LEDs can be accounted for by calibration, flux degradation due to aging can be monitored using optical sensors, and the drive current amplitude is kept constant in pulse width modulation driving, all color control concepts suffer from the detrimental impact of temperature variations of the LEDs on their color characteristics (Fig. 4).

Care is taken to ensure that these results are obtained for the actual junction temperature of the LED. The junction temperature of an LED can in principle be derived from its IV characteristics [2]. However, in actual LED lamps it is more usual to measure the temperature of the heat sink on which the LEDs are mounted and derive the junction temperatures of the LEDs using appropriate thermal models [9]. The impact of temperature is illustrated for the example of temperature feed forward. Simulations correlate the color point deviation

resulting from errors of the temperature measurement due to inaccuracies of the temperature sensor system (Fig. 5).

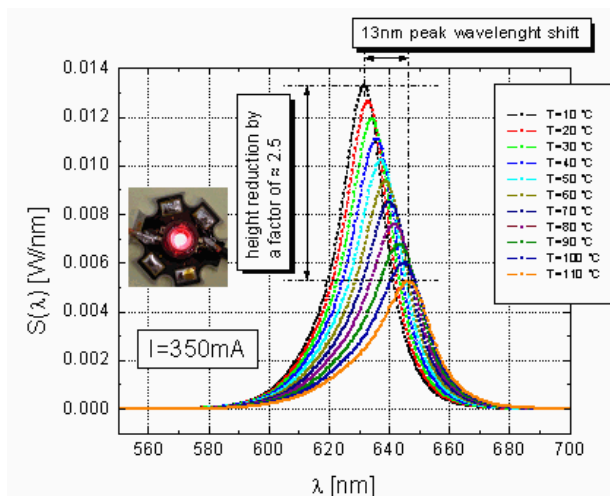


Figure 4. Effect of temperature variation on the spectral emission of a red 1W Luxeon LED [3].

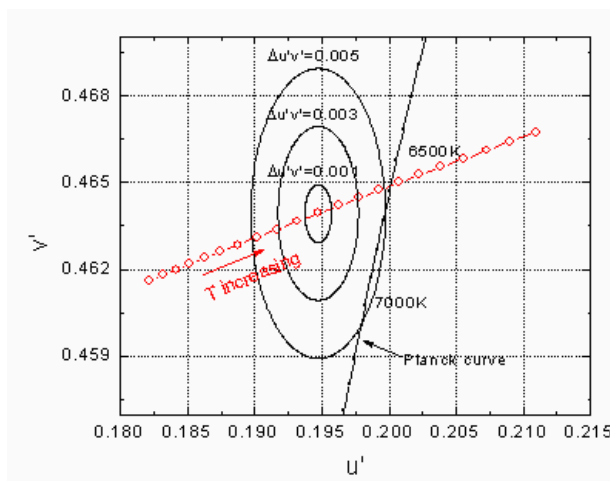


Figure 5. Color point deviations due to wrong temperature measurement of the red LED. The error in temperature is 2 °C from dot to dot on the red trace.

Although LEDs are most often operated using pulse width modulated drive currents with constant current amplitude, amplitude modulation of the LED current is of interest since the efficiency of currently available LEDs increases with decreasing current amplitude (Fig. 6).

Amplitude modulation results in a pronounced shift of the peak wave length of the LED spectra (Fig. 7) which has to be accounted for by the color control.

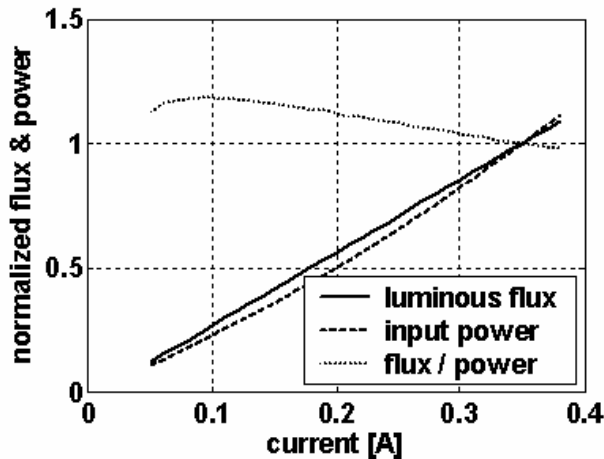


Figure 6. Relative luminous flux, electrical input power, and luminous efficacy (flux / power) versus current for Luxeon GaP (red, red-orange, amber) 1W LEDs [3].

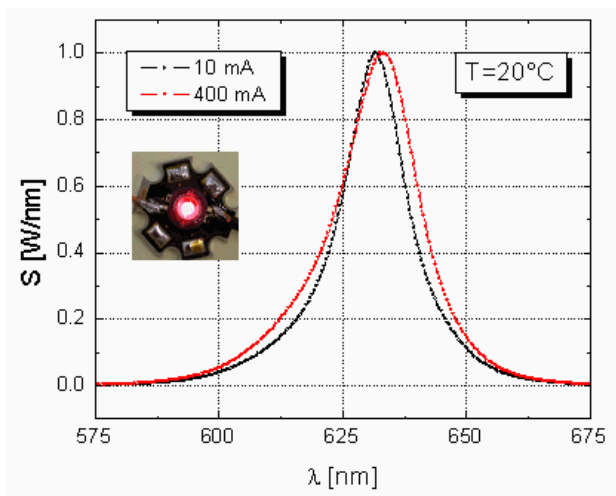


Figure 7. Effect of current variations on spectral shape of the emission of a red 1W Luxeon LED [3]. The spectra have been normalized to the same height in this figure for best clarity reasons.

IV. COLOR SENSOR CHARACTERISTICS

Currently, there is a strong interest in using color sensors to control the color temperature of LED based LCD backlights [8]. There are several color sensors commercially available [14-17]. Their functionality ranges from pure color sensors, via the integration of transimpedance amplifiers, to products with integrated signal processing that use a digital interface to communicate the measured color to the backlight control system. Hitherto, these sensors were used in applications where they were subject to moderate temperature rises well below 100°C. For the color control of LED lamps it is of interest to

integrate them into the lamps where they may be subject to elevated temperatures above their current specification. This will result in a modification of the sensor characteristics (Fig. 8).

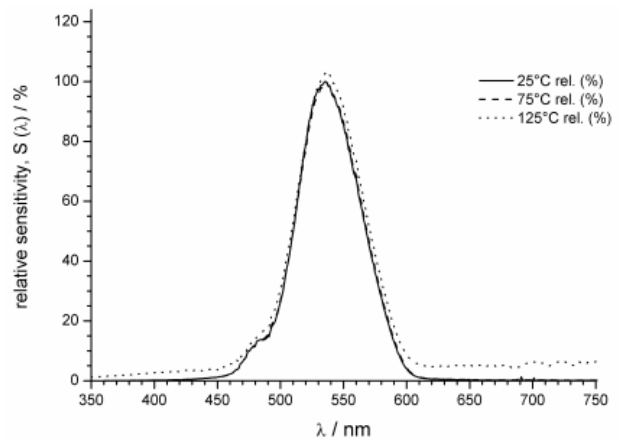


Figure 8. Sensitivity of the green channel of a commercially available color sensor measured at 25°C, 75°C, and 125°C. The latter is above its specified range of operation.

This effect is even more pronounced if next to the sensor also the sensor electronics is (partly) subjected to elevated temperatures (Fig. 9).

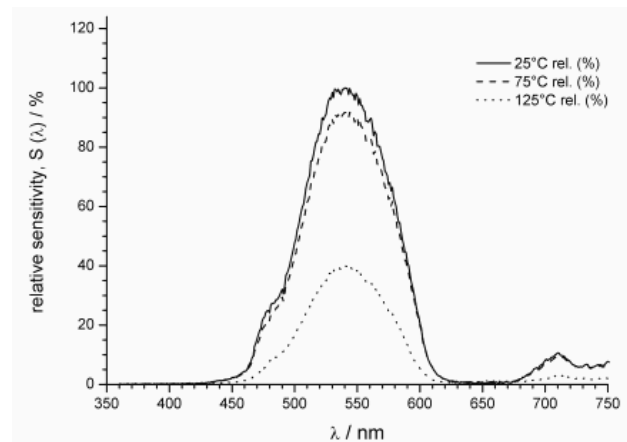


Figure 9. Sensitivity of the green channel of a commercially available color sensor with partly integrated electronics, measured at 25°C, 75°C, and 125°C. The latter is above its specified range of operation.

V. COLOR CONTROL IMPLEMENTATION

The first step for implementing the color control is to derive a functional block diagram (Fig. 10) from the schematic presentation of a LED lamp feedback color control system (Fig. 2). It is assumed that there is one set of optical sensors, i.e. a color sensor.

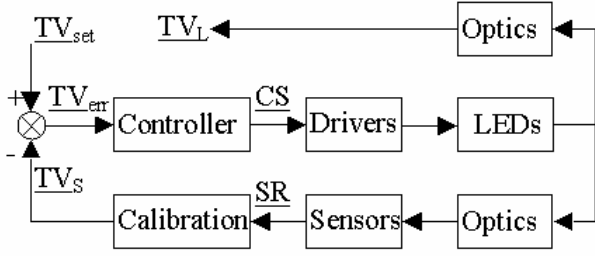


Figure 10. Functional block diagram of a LED lamp color feedback control system.

Tristimulus values $\underline{TV}=(X, Y, Z)$ are used to express the brightness (Y) and chromaticity coordinates ($x=X/(X+Y+Z)$, $y=Y/(X+Y+Z)$) of the target light $\underline{TV}_L$ and the colored LEDs. Replacing the functional blocks by corresponding transfer functions results in the transfer function block diagram of the control system (Fig. 11).

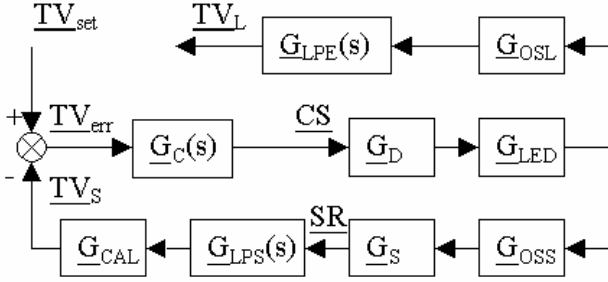


Figure 11. Transfer function block diagram of a LED lamp color feedback control system.

A controller $\underline{G}_C(s)$ determines control signals $\underline{CS}$ for the LED drivers $\underline{G}_D$, e.g. current amplitudes or duty cycles for pulse width modulation (PWM), from the difference $\underline{TV}_{err}$ between desired $\underline{TV}_{set}$ and measured $\underline{TV}_S$ tristimulus values such that this difference is minimized. Due to manufacturing spread of the LEDs $\underline{G}_{LED}$, the specific properties of the color sensor $\underline{G}_S$, and different optical paths from the LEDs to the sensors $\underline{G}_{OSS}$ and to the light emitted by the lamp $\underline{G}_{OSL}$, calibration $\underline{G}_{CAL}$ of the sensor readings $\underline{SR}$ is required to make the measured tristimulus values $\underline{TV}_S$ equal to that of the emitted light $\underline{TV}_L$. The human eye acts as a low pass filter $\underline{G}_{LPE}(s)$ with a corner frequency of less than 100 Hz. Therefore, especially for implementing chromaticity coordinates feedback which is dealt with here, the sensor signals are low pass filtered with a corner frequency less than 10 Hz. As a consequence of this, only the dynamics of the controller $\underline{G}_C(s)$ and the low pass filters for the sensor signals $\underline{G}_{LPS}(s)$ need to be taken into account when designing the control.

Sensor readings $\underline{SR}$ and light output $\underline{TV}_L$ (using a spectrometer) are determined as a function of the control signals $\underline{CS}$ created by the controller in the steady state, i.e. neglecting the low pass filters. The results of this calibration

process are summarized in the transfer functions $\underline{G}_{C2T}$ and $\underline{G}_{C2S}$.

$$\underline{TV}_L = \underline{G}_{OSL} \cdot \underline{G}_{LED} \cdot \underline{G}_D \cdot \underline{CS} = \underline{G}_{C2T} \cdot \underline{CS} \quad (1)$$

$$\underline{SR} = \underline{G}_S \cdot \underline{G}_{OSS} \cdot \underline{G}_{LED} \cdot \underline{G}_D \cdot \underline{CS} = \underline{G}_{C2S} \cdot \underline{CS} \quad (2)$$

From (1), (2), and the block diagram (Fig. 11) of the control system it can be concluded, that the sensed tristimulus values $\underline{TV}_S$ being equal to that of the light emitted by the lamp $\underline{TV}_L$ requires

$$\underline{G}_{CAL} = \underline{G}_{C2T} \cdot \underline{G}_{C2S}^{-1} \quad (3)$$

Using the relations (1) to (3) the block diagram depicted in Fig. 11 is simplified as shown in Fig. 12.

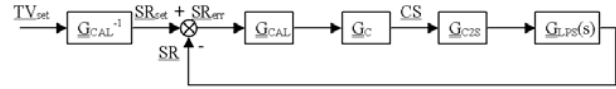


Figure 12. Simplified block diagram of the LED color control system.

This Multiple Input Multiple Output (MIMO) control is implemented by decoupling the control signals and sensor readings for the different colours. This is achieved by choosing

$$\underline{G}_C \cdot \underline{G}_{CAL} = \underline{G}_{C2S}^{-1} \cdot \underline{G}_{dyn}(s) \quad (4)$$

Then the structure of the system simplifies as depicted in Fig. 13.

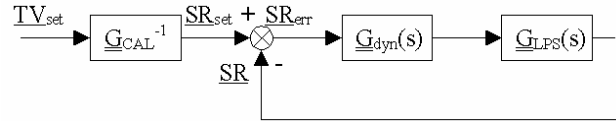


Figure 13. Block diagram of the decoupled LED color control system.

Each color sensor has its own low pass filter. Therefore, $\underline{G}_{LPS}(s)$ and thus also $\underline{G}_{dyn}(s)$ are diagonal matrices. The elements of $\underline{G}_{dyn}(s)$ can be designed independent from each other, using e.g. PI controllers as described in [6].

Fig. 14 shows the implementation of this controller in Simulink. The blocks DS2001 and DS2102 in the block diagram represent I/O boards of the dSPACE rapid control prototyping system (chapter VI) that are used to connect to the driver board and sensor board, respectively.

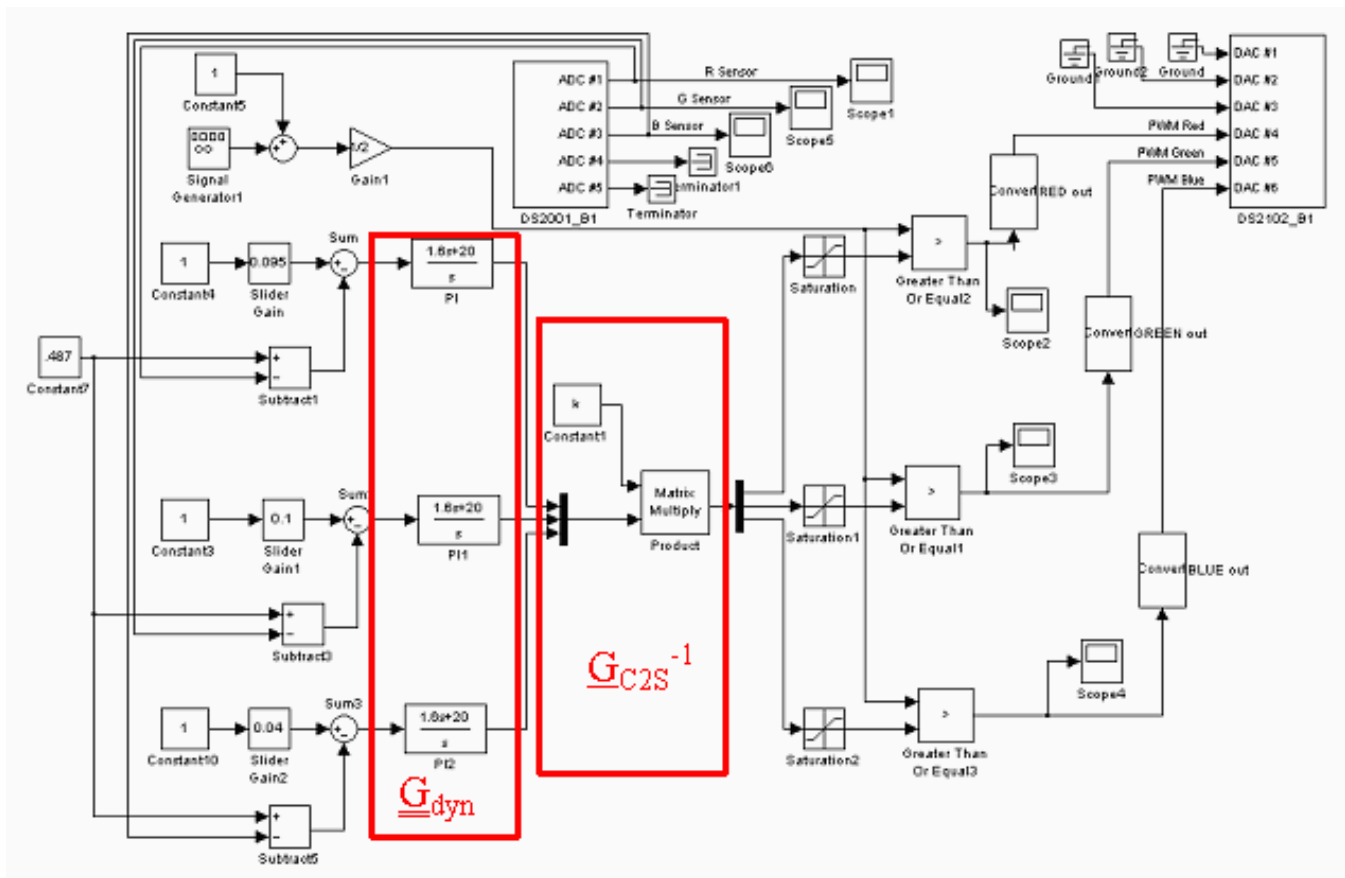


Figure 14. Implementation of the controller in Simulink.

VI. RAPID CONTROL PROTOTYPING SYSTEM

A rapid control prototyping (RCP) system has been set up to implement, evaluate, and optimize feedback color control of an experimental LED lamp (cf. e.g. [18] for RCP). The software and digital hardware commercially available from dSPACE [19] is used in conjunction with custom in-house developed hardware. The dSPACE RCP system makes use of the well-known MATLAB/Simulink [20] simulation software. Comprehensive information about these tools is available on the homepages of the companies providing them.

Automatic code generation from controller block diagrams allows for seamless transition from off-line simulation to real-time operation on the embedded controller. Easy data access and visualization and on-the-fly parameter tuning provide insight into controller performance and facilitate its optimization.

The control algorithms are implemented as Simulink block diagrams (Fig. 14). Code is generated automatically from the Simulink model and downloaded to the embedded controller on the dSPACE real-time hardware. Furthermore, the real-time hardware comprises D/A and A/D boards that provide interfaces to the LED drivers and the sensor electronics (Fig. 15).

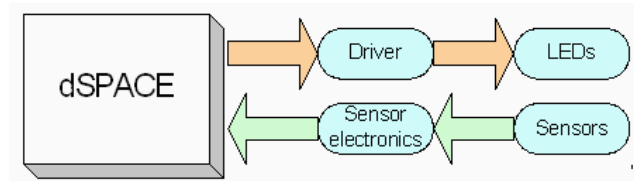


Figure 15. Rapid control prototyping system block diagram.

Drivers, experimental LED lamp, and sensor boards (Fig. 16) attached to the system have been custom made.

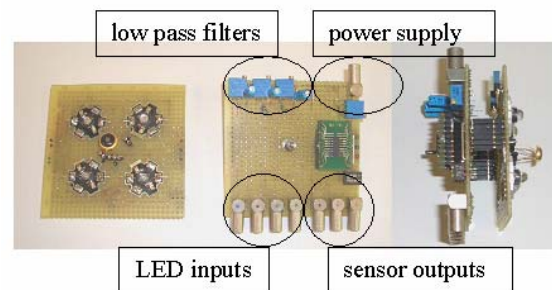


Figure 16. LED lamp and sensor boards.

A MAZeT [16] color sensor MTCSiCT and transimpedance amplifier IC MTI04CS are used for color sensing. The experimental LED lamp comprises one red, one blue, and two green Lumileds Luxeon I LEDs [3].

LED and sensor boards are mounted in an integration sphere (Fig. 17) that is used to mix the light. A spectrometer is connected to it for calibrating the LED lamp and determining the color accuracy achieved by the control system under different operating conditions.

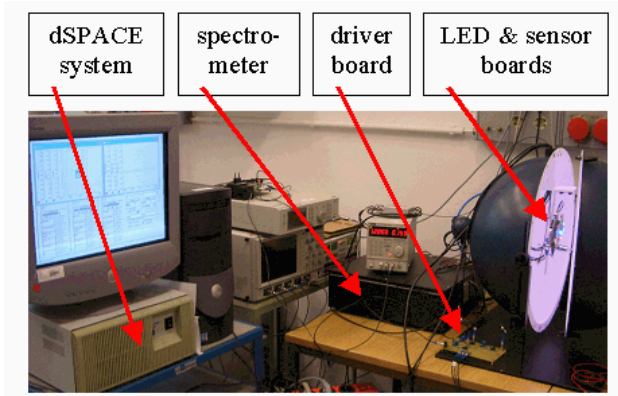


Figure 17. Rapid control prototyping laboratory setup.

Using the dSPACE tools, a control interface (Fig. 18) has been created to access and visualize data from the real-time hardware and modify parameters while the experiment is running.

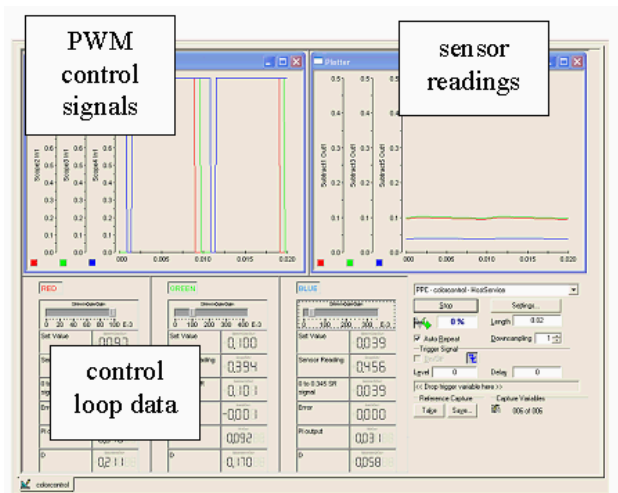


Figure 18. Experiment control interface.

VII. COLOR CONTROL VALIDATION

Virtually any of the color control concepts outlined in chapter II can be implemented, optimized, and evaluated using rapid color control prototyping. For each concept the sensors needed have to be mounted in the LED lamp and interfaced to

the real-time hardware. Thereupon all further adjustments required can be made in the block diagram representation of the controller (Fig. 14) and the experiment control interface (Fig. 18). Fig. 14 and Fig. 18 refer to using chromaticity coordinates feedback control in conjunction with pulse width modulation of the LED currents.

The experiment has also been adapted to chromaticity coordinates feedback control used in conjunction with pulse width modulation of the LED currents. This required only a few changes to the block diagram (Fig. 14) and control interface (Fig. 18) not shown here in detail. The system was calibrated as outlined in chapter IV. Then it was commanded to create light with a set of color points located in the vicinity of the black body line. The chromaticity coordinates of the light actually produced were measured using the spectrometer attached to the experiment (Fig. 17). The color accuracy achieved with the setup is depicted in Fig. 19.

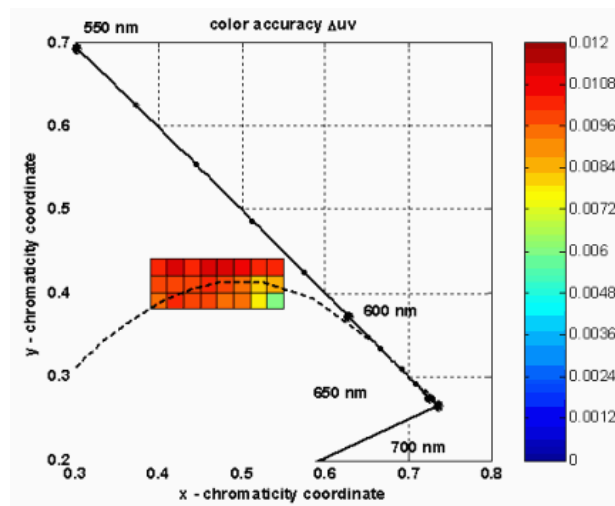


Figure 19. Color accuracy achieved with RCP.

Each square corresponds to one measurement taken for the target color point located at its center. The color accuracy is expressed as the difference Δuv between target and measured light according to the color scale in Fig. 19 as outlined e.g. in [4]. The accuracy achieved is in the range of target values for general illumination [4].

VIII. CONCLUSIONS

Color accuracy of white light generation is one of the key challenges lying ahead for solid-state lighting entering the general illumination market. Color control concepts have been reviewed. Temperature characteristics of LEDs and color sensors have been discussed. Implementation of color control concepts has been outlined and it has been shown that rapid color control prototyping is well suited for evaluating, implementing and optimizing the different concepts. Quantitative results are given for a specific example.

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