JENCOLOR

1. Introduction

The importance of LEDs increases with every progress. Smaller packages, higher efficiency and light output, innovations with additional optics and several selectable wavelengths within the visible spectrum open more and more markets for lighting systems based on LEDs. However, LEDs have to handle against some disadvantages. A significant one is the drift of wavelength and brightness due to a change of temperature and ageing effects. Without compensation the rise of temperature from 10°C to 85°C produces on its own a color difference of $\Delta u'v' = 0.0255$ measured for the white point in a lighting system based on red, green and blue LEDs. Considering to the limit of $\Delta u'v' = 0.005$ visible for the human eye, these effects cannot be disregarded in lighting devices with the requirement of constant colors.

The MAZeT GmbH offers user-specific electronic designs with True Color sensors, standard and application specific microcontrollers. So customers can build up the color control with their own competence, while MAZeT GmbH provides the possibility of software support for calibration and value adjustment for True Color sensors.

Among others MAZeT recommends a “plug and play” sensor solution for a LED control using the Avago Technologies “Color Management System Feedback Controller” *HDJD-J822-SCR00.* This integrated circuit plus a color sensor IC has the possibility to control chromaticity coordinate and brightness of lighting systems based on multiple colored (RGB) LEDs. Through the connected color sensor the color controller receives response of the actual color and regulates a pre-adjusted color (target color) self-contained with an accuracy depending on the sensor characteristics.

This article describes a benchmark to compare RGB and True Color sensors combined with the color controller *HDJD-J822-SCR00*. The comparison is based on the *ADJD-E622-QR999* RGB color sensor and the *MTCS-TIAM2* True Color sensor based on the standard observer function “like human eye”.

2. Functionality of color sensors

The most conventional sensor technology for color sensors is the tristimulus method based on RGB or other spectral filters which are implemented as interference or absorption filters. Color sensors of MAZeT are based on high-quality interference and XYZ spectral filters which defines that the output

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values of the detector emulate the tristimulus value function of the human eye (Values are defined in the CIE 1931 color space).

After being amplified and digitalized, the three detector signals approximate the tristimulus values XYZ. Compared to spectrometers, color sensors present a cost-effective solution for the measurement and control of illumination. They can be designed with absorption or interference filter in front of a light sensitive detector. Some main characteristics of the several filter types are listed in Table 1 and 2.

Characteristic	Absorption filter	Interference filter
Maximum transmission in the transmission range	Typical Range 60…70%	> 95%
Remaining transmission in the cut-off region	Typical Range 10…20%	< 1%
Temperature stability	Dependant on filter material	Independent from temperature – high temperature stable
Transmission characteristic	Aging due to absorption	Long-term stability without drifts

Table 1: Comparison of absorptions and interference filter

Filter	RGB	XYZ (True Color)
peak/position/ sensitivity	equally shared in VIS based on used filter material	tri-stimulus function - standard observer function (CIE 1931, DIN5033)
interface	red, green blue part of incoming – any status	Yxy, L*u'v' coordinate in color space
applicable for	color teaching and detection	absolute or relative color measurement with an accuracy of $\Delta u'v' < 0{,}005$ (like human eye)

Table 2: Comparison of RGB and XYZ filter

The MAZeT XYZ sensor IC MTCSiCS is worldwide the unique color sensor which realizes the tristimulus value function using a combination of photodiode and interference filter. In consequence, the three output voltages of the MTCSiCS present XYZ based values. A comparison of the three resulted filter functions $x_{MTCSiCS}(\lambda)$, $y_{MTCSiCS}(\lambda)$, $z_{MTCSiCS}(\lambda)$ and of a typical RGB color sensor[1] r(λ), g(λ), b(λ) is shown in Figure 1.

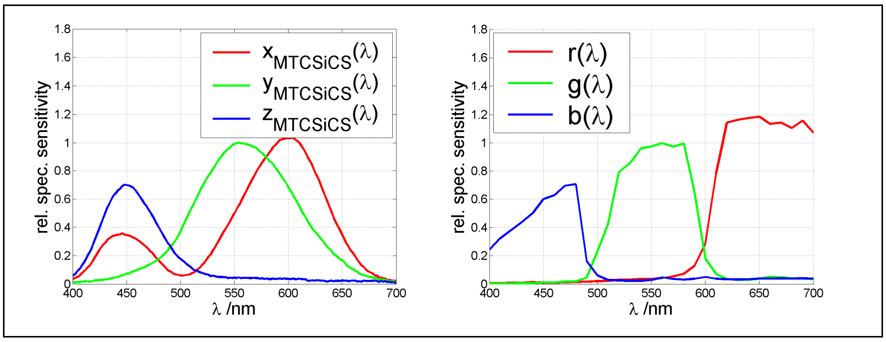

Figure 1: Filter functions of true (left) and RGB (right) color sensor

Incident light, for example from a multicolor LED (RGB LED), causes a photo current depending on the illuminance of the light source. The following electrical amplification converts the current into voltage which is digitalized for calibration and signal processing. The software is realized in a microcontroller and/or PC (Figure 2).

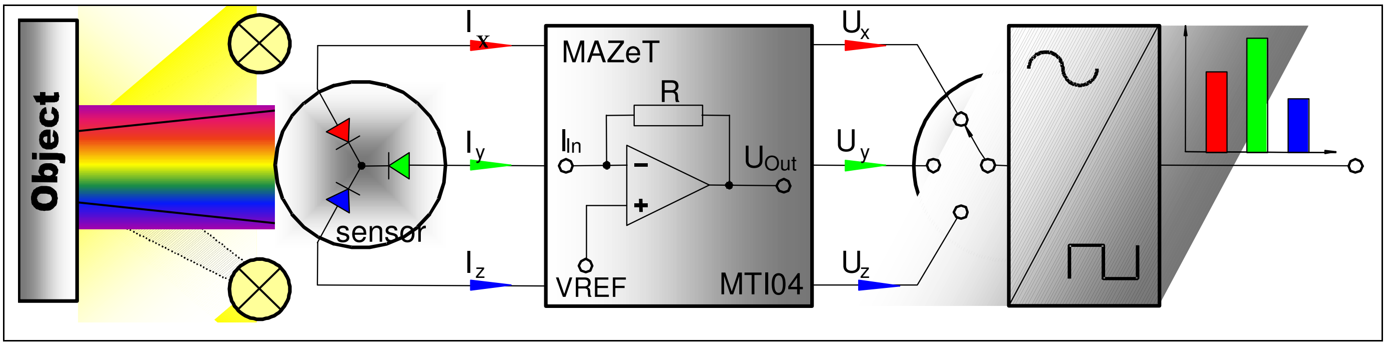

Figure 2: The way from light to XYZ

The resultant XYZ tristimulus values can be computed in other color spaces, for example Yxy or L*u'v' CIE 1976, where Y and L* are measures for the brightness and xy and u'v' for the chromaticity coordinate. These two color spaces are usually used for self-illuminating targets. Depending on the coloring, the human eye can differ between two colors down to a color difference of Δu'v' = 0,005 (for average eyes, trained ones see as different until 0,003) and a brightness of 4%. These values are

[1] e.g. different alternatives on the market

mainly criteria for the quality and success of color control for RGB LEDs. The following text consults the color space L*u'v'.

The reference value L*u'v'(r) for a color control can be set manual or measured by a second color sensor focused on another LED or display to reproduce it. The actual color of the LED is measured with a color sensor in XYZ and computed to L*u'v'(a). According to the difference L*u'v'(r) – L*u'v'(a), a proportional controller sets the new PWM duty cycles for the red, green and blue LED until L*u'v'(r) is reached.

The different color gamut of multicolor LEDs must be subject of particular consideration. Reference values could not be reached if several multicolor LEDs are controlled with a reference value, chosen in border areas of the gamut. In this case, a smaller gamut should be selected.

A possibility other than color sensors is the control by measuring the junction temperature. This method, however, requires the knowledge of the exact behavior of the temperature. Therefore, the luminous flux over temperature must be determined for each LED to compensate the temperature effect during operation mode. Furthermore, aging must be compensated by measuring each LED at a defined temperature and adjust the difference to a reference value. Another disadvantage is the sole use of pulse width modulation controlled LEDs, due to the additional shift of the dominant wavelength according to the forward current, which cannot be controlled by measuring the junction temperature.

The next table lists some alternatives of color control:

Measurement	Advantages	Disadvantages
None	▶ Low cost	▶ Non constant color point over temperature and aging effects
Temperature	▶ Only one simple thermal sensor ▶ Calculating based on a-priori knowledge of wavelength shift and degreasing of intensity	▶ No optical measurement ▶ Measurement of parasitic parameter ▶ No detection of aging effects and damage effects ▶ Hysteresis of temperature coupling

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Measurement	Advantages	Disadvantages
Intensity	▶ Only on simple optical sensor ▶ Calculating based on a-priori knowledge of depending of degreasing of intensity and wavelength shift	▶ Optical measurement ▶ No color measurement ▶ No detection of aging effects and damage effects
RGB color	▶ measurement of mixed color effects ▶ Measurement of RGB effects and Intensity of RGB values	▶ No real color measurement ▶ Worse interpretation of color point ▶ two additional sensing channels
XYZ color	▶ Real measurement of mixed color ▶ Measurement of real color coordinates and brightness	▶ two additional sensing channels

Table 3: Measuring methods of color control

3. Color control of a backlight panel

By means of several simulations it is proved, that True Color sensors have a higher accuracy than RGB color sensors. In consequence, the accuracy is affected in color controlled LED systems, where the chromaticity coordinate and brightness are in dependency to temperature changes.
To test the differences of a color control with RGB or True Color sensors one system is built up with the *HDJD-J822-SCR00* and the *ADJD-E622-QR999* RGB sensor of Avago Technologies and a second one with the same controller and the *MTCS-TIAM2* True Color sensor of MAZeT GmbH. To receive representative results both sensors are connected as described in the corresponding data sheet or application notes. Differences between both sensors are listed in Table 4.

	MTCS-TIAM2	*ADJD-E622-QR999*	Design modification
Amplification stages	Eight common stages for the three channels X, Y and Z.	Eight stages for each channel R, G and B.	Six additional I/O pins for the *ADJD-E622-QR999* to use all possible stages.
Mode of operation	2,5V reverse voltage connected to the common cathode.	Zero bias – 0V connected to anodes.	MTCS-TIAM2 connected with additional 2,5V voltage.

Table 4: Differences in design between *MTCS-TIAM2* and *ADJD-E622-QR999*

The *HDJD-J822-SCR00* can handle with both sensors. The rest of the circuit is identical. The LED system is cooled or heated from 10°C to 85°C to provoke drifts of the chromaticity coordinate and brightness. A spectrometer measures the LED color independent from the color sensors to compare the L*u'v' values with a given target color. If the limit of $\Delta u'v' \leq 0.005$ is maintained a control is successfully completed.

The used backlight panel consists of twelve red, 24 green and twelve blue LEDs (Figure 3) each driven with 12bit pulse width modulation at 350mA forward current. As well as the LEDs the color sensor is placed behind a diffuser focused on its centre. In front of the diffuser the spectrometer is positioned for calibration and measurements during the control.

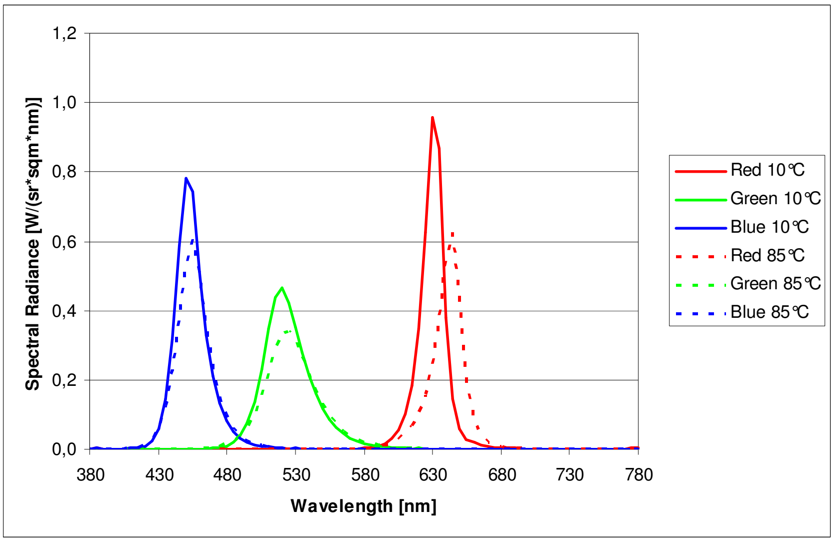

Figure 3: Osram LD/LT/LR W5KM Golden DRAGON® ARGUS®, deep blue/true green/red

The test is divided in two runs each performed with the *MTCS-TIAM2* and *ADJD-E622-QR999*. In the first run the lighting system is calibrated at 40°C. Afterwards the target colors 1 to 4 are controlled at 20°C, 40°C and 70°C. The calibration for the second run is executed at 10°C and the following controls are done in 5°C steps up to 85°C with target color 5.

Number	Target color	L*	u'	v'	(CCT)
1	D65	5932.2	0.1980	0.4680	6504K
2	C	5932.2	0.2010	0.4610	6744K
3	7500K	5932.2	0.1960	0.4560	7500K
4	5000K	5932.2	0.2110	0.4850	5000K
5	White	5715.9	0.2100	0.4730	---

Table 5: target colors for the runs (CCT = Correlated Color Temperature)

4. Results of the test between RGB and True Color sensors

As mentioned above, a color control is only successful, if the color difference between target color and controlled color is under Δu'v' ≤ 0.005. This limit indicates the distance of two colors visible with the human eye. "Trained eyes" can see differences of 0.003.
Due to the comparable behavior of color control for all target colors, the following report is reduced to D65 and white.

Result for D65:

		Difference to target color			Difference of
		20°C	40°C	70°C	20°C to 70°C
ADJD-E622-QR999	**Δ** L*	-8.1%	-4.0%	1.1%	9.9%
	Δ u'v'	0.0070	0.0017	0.0077	0.0147
	Δ CCT	409K	68K	-567K	-976K
MTCS-TIAM2	**Δ** L*	-6.8%	-3.1%	6.8%	14.6%
	Δ u'v'	0.0011	0.0013	0.0008	0.0017
	Δ CCT	-125K	-76K	-95K	30K

The RGB color sensor *ADJD-E622-QR999* is only successful at 40°C, by reason of the calibration at the same temperature. In this case, there is no shift of the wavelength or brightness existent. The difference between 20°C and 70°C is added up to a factor of three above the acceptable limit of 0.005. The MTCS-TIAM2 True Color sensor sticks to the limit over the complete temperature range. Figure 4 illustrates the result (blue circle indicates Δu'v' = 0.005).

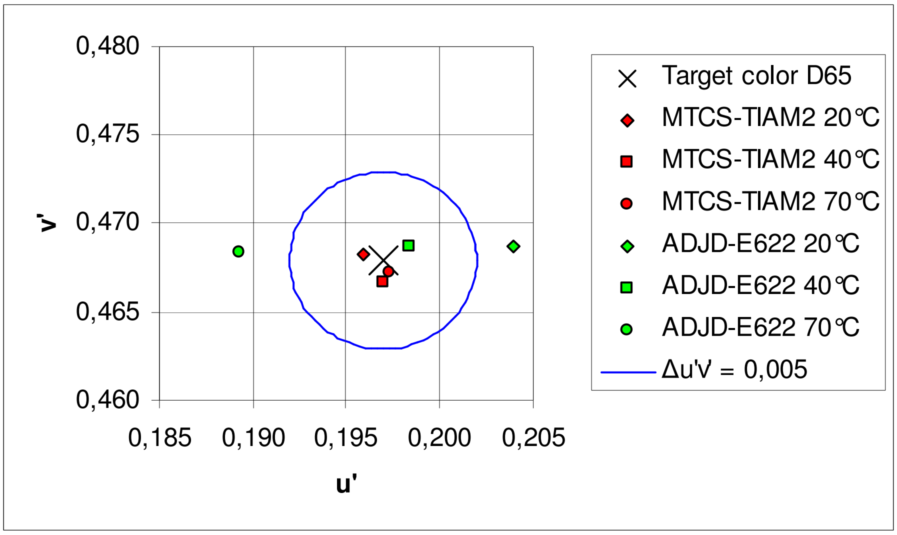

Figure 4: Result for target color D65

An expanded temperature range clarifies the difference between RGB and True Color sensor as tested with the target color white (Figure 5). In the range of 10°C to 85°C the *ADJD-E622-QR999* produces a Δu'v' of 0.0226, while the MTCS-TIAM2 reaches of 0.0030.

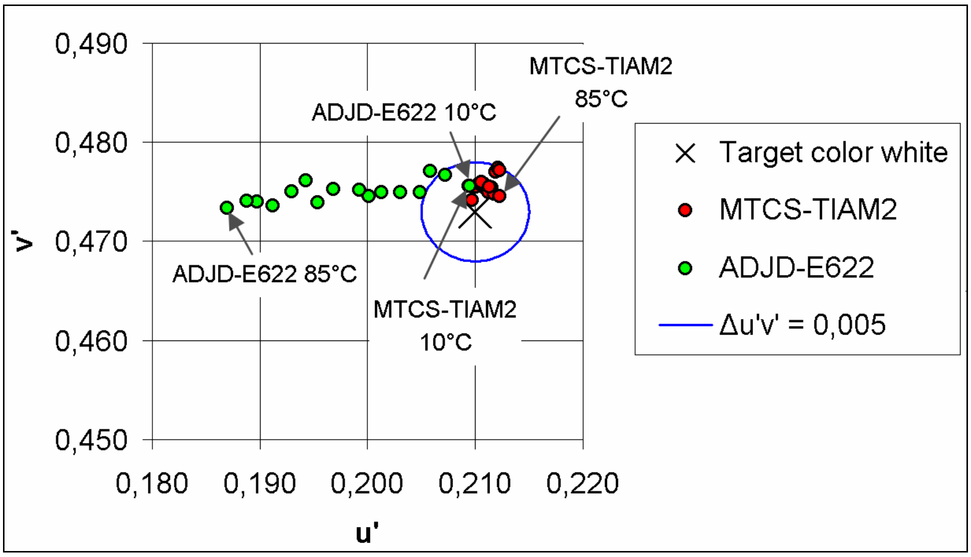

Figure 5: Result for target color white

5. Summary

By means of a backlight panel based on several RGB LEDs it is shown that a color control with the *HDJD-J822-SCR00* color management controller of Avago Technologies combined with the *MTCS-TIAM2* True Color sensor of MAZeT GmbH works effective in expanded temperature ranges. The resultant accuracy reaches values not visible with the human eye. In contrast, the *ADJD-E622-QR999* RGB color sensor already attained a mean Δu'v' of 0.0067 at temperature changes of 20°C. Variations of 75°C caused color differences of even 0.0226, while the True Color sensor produces a maximum Δu'v' of 0,0030.