Optical and Thermal Characteristics of Colour Sensors for usage in multichannel LED Luminaires

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LEDs nowadays are widely used for special lighting for signalling and backlight purposes like for example traffic lighting, rear lighting, headlamps in automotive and in monitors. In the last decade the interest in LEDs for generally lighting has risen due to their potential of energy saving and the possibility of changeable colour inside the span of the chosen LED colour points i.e. the gamut. Based on this possibility of colour changeability general lighting evolves into a dynamic and human adapted lighting. Therefore it should be possible to change the generated white light from cold to warm white, while maintaining for example the Colour Rendering Index high.

But LEDs are not without flaw. During the production processes discrepancies between LEDs occur, which results, for the emitted light, in different points in colour space, so that they have to be binned. Also it is well known that a change in temperature and ageing of the LEDs lead to a detectable and often not acceptable colour shift.

To compensate these deficiencies colour control algorithm are used. One possibility to do so is using colour sensors to detect the actual colour point of the individual luminaire, and then control it via an appropriate algorithm.

1 Introduction

This Paper describes two different measurements to characterise the behaviour of the colour sensors for different application conditions in multichannel-LED-luminaires. Therefore a characterisation setup is built to get the sensor respond functions with different temperatures and viewing angles. Different colour sensors for light applications are chosen. All Sensors communicate via an i²C-protocol [3].

In this work a colour sensor is defined as a three channel colour sensor consisting of the channels R, G, B or X, Y and Z, i.e. red, green, blue and the tristimulus values X, Y and Z of an observer at 2° (CIE-1931) respectively. These sensors are commonly used for backlight applications in monitors, for example. Using them inside LED-luminaires changes their usual environmental conditions to higher temperatures up to 90°C and eventually higher spectral irradiances. Due to this fact it is crucial to know the changes which can occur while reading the sensor data for different environmental conditions. We are going to show the discrepancies during the production. Furthermore we examine the response function of different types of colour sensors under four different temperatures and three different angles of incidence. Afterwards the consequences of the measured results for a colour feedback control in LED-luminaires is discussed. Why should one use colour sensors instead of spectrometers? Spectrometers decompose the light by using dispersion elements, i.e. a grating or a prism, which allows very narrow passbands. Spectrometers allow very accurate measurements with the flaw to be expensive and susceptible to
interferences. In contrast, colour sensors use the colorimetric method, which means that the colour is analysed by a set of three primaries, i.e., the three channels red (R), green (G), and blue (B). This ensures a simpler implementation, a faster calculation, and makes it much more cost-effective. The RGB outputs of the sensors are directly comparable with the human vision response [4].

2 Measurement Setup

A measurement setup fig.: 1 is built using a Xe-Lamp (LOT) due to the spectral characteristics, supplying enough light in the whole visible range. So that a Czerny-Turner monochromator can be used to decompose the Xe-Spectrum into radiation with a 3nm bandwidth[1, 5]. At the Czerny-Turner monochromator a high reflective integrating sphere (labsphere) is directly flanged, to minimize the optical path from the monochromator to the integrating sphere. The integrating sphere is used to homogenise the incoming light. At one of the two output ports (spectrometer port) of the integrating sphere an optical fibre is mounted which leads the incoming light to the spectrometer (CAS 140b-Instrument Systems). The other output port (sensor port) is arranged at 90° to the spectrometer port and can be used for example to obtain the spectral response functions of camera sensors or colour sensors. In front of the sensor port a neutral glass filter wheel is positioned, to measure the linearity of the sensors. Also different pinholes can be integrated to alter the angle of incidence of the sensed light.

The colour sensors are installed on a thermally changeable and stabilized mount. This is realised by using a Peltier element, a temperature sensor (PT100) and a temperature controller (TEC-Controller Thorlabs). To get a high thermal conductivity to the sensors, to assure that the sensors have the right temperature, the colour sensors are soldered to an aluminium core board. The surface is blackened, to avoid reflections as good as possible, and the design is for every colour sensors the same. The colour sensor mount is then positioned via a slider with a millimetre scale. This together ensures the same conditions for every measurement.

fig.: 1 A schematic of the colour sensor/ image sensor measurement setup.
3 Colour Sensors

We use five different commercial available colour sensors, all of them using the I2C-protocol. With two fundamentally different filter methods. One kind of filter relies on absorption, which means they are normally made with a defined glass substrate to block the not wanted wavelength of incoming radiation by absorption and transmit the necessary wavelengths. This means that the unwanted radiation is maintained inside the filters, what can lead to an ageing of the material, leading to an ageing of the whole sensor. The Advantage of these filters are mostly impervious for a change in angle. In comparison a dichroic filter uses interference to reflect the unwanted light and transmit the needed radiation via constructive interference. Dichroic filters have the disadvantage of being extremely angle sensitive but have the advantage to be able to duplicate for example the tristimulus functions of the CIE standard observer [2].

All of the used sensors are soldered to a universal designed aluminium core board with 30mm x 30mm (fig.: 2). The sensors are positioned at the same point, which is defined by the middle of the output port of the integrating sphere.

4 Experimental Results and Discussion

For calculating the objective points in colour space detected by the sensors, the relative curves of the colour sensors are the important ones. These are measured with the help of the above mentioned measurement setup and a MSP432 Launchpad from Texas Instruments to read the sensor respond functions. These functions are then devided by the incoming monochromator spectrum and afterwards normalised to the green (G) or the (Y) channel for the absorptive sensors and to the dichroic sensors respectively. The XYZ-sensors will be named A and B and the four RGB-colour sensors C to E. The angle of incidence was changed with different pinholes between the light source and the colour sensors. In figure (fig.: 3) sensor A is measured with three different angles of

![Five used colour sensors with a five euro cent in the right upper corner to compare the size.](image-url)
incident, as it is a sensor with dichroic filters a sensitivity shift to lower wavelength is expected when increasing the angle of incidence. Only a slight change is measured at an observation angle of 40°. Which could give the idea of the expected. To verify the shift an additional measurement was performed with 75° of incidence angle (fig.: 4). Here the shift is significant and shows how the whole sensor sensitivity changes to smaller wavelength.

fig.: 3 Sensor A measured at three different angles of incidence, i.e. 5°, 12°, 40°

fig.: 4 Sensor A measured at 2 different angles of incidence to verify the sensitivity shift.
As this changes the relative curves this will affect the measured colour, to get such an high angle of incidence we had to use a pinhole with a diameter of 3.8 cm. Sensor B behaves similar and therefore only the low angles of incidence are shown (fig.: 5). With the result that for angles of incidences up to 40° is acceptable if the light source lies in the optical axes.

fig.: 5 Sensor B measured at three different angle of incidence, i.e. 5°-, 12°-, 40°- observer.

For comparison we can see that for an RGB – sensor using absorption filters the angle of incidence does not affect the relative sensor response (fig.: 6). If we compare both fig.: 5 and fig.: 6 with each other we can see the different respond functions. The XYZ – sensors try to mimic the tristimulus values of the CIE-1931 standard observer and the RGB-sensors try to span the whole visible range to be able to detect nearly every colour.
fig.: 6 Sensor C measured at three different angle of incidence, i.e. 5°-, 12°-, 40°- observer. No change in sensor response is detectable.

Due to this fact the metameres of the RGB-Sensors are very different to the standard observer, while the XYZ-sensor has almost the same metameres. Leading to different problems whilst detecting different spectra.

Next we compared different sensors of sensor B of the same batch with each other (fig.: 7).

fig.: 7 Three different sensors B of the same batch. Plotted is the difference in the u'v'- colour space. In the inlay the different sensor respond functions are plotted. In black are the coordinates before calibration. In red after calibration for the sensor B-1.
First we wanted to see how much the raw sensor data varies from the CIE-standard observer, this is plotted in black. The maximal variations to the spectrometer is for sensor B-3 and is $\Delta u'v' = 0.012$ and the minimal distance $\Delta u'v' = 0.004$ for sensor B-1. After using a calibration matrix for sensor B-1 plotted in red the distance for this sensor reduces to $\Delta u'v' = 0.00098$. For the other sensor the distance is also reduced but the distance to Sensor B-3 is still $\Delta u'v' = 0.0089$.

That means that even by using XYZ-sensors a calibration matrix for every individual sensor is necessary and cannot be omitted.

The other great issue using colour sensors in led-luminaires is the temperature behaviour of these. Therefore we measured every sensor at four different board temperatures, i.e. 25°C, 40°C, 60°C and 80°C. In (fig.: 8) we can see the temperature measurement for sensor D. While the raw sensor data for 25°C and 40°C does not differ, the sensor response for 60°C is reduced. If we look at the 80°C Data, the respond functions get nearly to zero.

If we now calculate the relative respond functions see (fig.: 9) we can see that even so the 60°C – values are reduced the relative curves overlap pretty well. But the Data for the 80°C differs a lot in the red and the blue channel leading to a not existing drift in colour space while measuring at these high temperatures.

![Sensor D response values for four different Temperatures.](image)
For Sensor C we can see in the following figure (fig.: 10) that the respond function of every channel of Sensor C gets smaller while the temperature rises. But in comparison to Sensor D the change of the relative sensor curves in (fig.: 11) do not vary except for a little area in the green channel, which leads to a more or less steady calculation in colour space even by varying the temperature. The light intensity which will be measured will be affected in such a way that the sensed light is brighter than measured with this sensor at 80°C due to the decreasing sensitivity.

Last we examined the temperature behaviour of the sensors using the dichroic filters. Figure (fig.: 12 Sensor A respond values for four different Temperatures.fig.: 12) shows the raw sensor data of Sensor A which is recorded while changing the board temperature of the colour sensor from 25°C to 80°C. In contrast to the colour sensors with absorption filters the change in temperature does not really affect the sensor respond functions. Calculating the relative sensor values of Sensor A in (fig.: 13) results in a complete overlap of the sensor values for the four different Temperatures. This behaviour can also be seen for Sensor B where the sensor curves also overlap in the range of the measurement uncertainty. This behaviour is counter intuitive as one would expect an expansion of the filter because of the temperature increase and also like the RGB-sensors a change due to the change in the used silicon. The used filter materials are not temperature sensitive in the measured temperature range and the silicon behaviour is compensated by an integrated temperature and an integrated lookup table.
fig.: 10 Sensor C respond values for four different Temperatures.

fig.: 11 Sensor C relative respond values for four different Temperatures.
fig.: 12 Sensor A respond values for four different Temperatures.

fig.: 13 Sensor A relative respond values for four different Temperatures.
fig.: 14 Sensor B respond values for four different Temperatures.

fig.: 15 Sensor B relative respond values for four different Temperatures.
5 Conclusion

Colour sensors in both forms are suitable to use for colorimetric purposes. In the present paper it has been shown that both types of colour sensors using dichroic or absorption filters can lead from good to very bad results according to the wanted tasks. While the RGB – colour sensors, which are using absorption filters are mostly independent of angle variations, dichroic filters have the advantage of not absorbing radiation with the lack of potential of ageing. The angle dependency of the dichroic filters is a problem when integrating the sensor in the nearfield of the light source.

Both types of sensors are temperature dependent, but not due to the filters, here the used photodiodes are responsible for the change of the colour sensor respond functions. This could be overcome by an integrated temperature sensor and an integrated compensation lookup table, like used by sensor A and sensor B. The quality to measure light properly is also very dependent on the calibration for the used sensor. Some sensors seem to be much more stable like sensor C in comparison to sensor D during the measurement. And also during the temperature changes. The colorimetric calculation for every variation has still to be calculated to make a quantitative estimation of the measured colour change due to the change of the respond functions. A change in time is still to be investigated to get information about ageing of the colour sensors. Integrating the colour sensors in a working feedback control in luminaires could give better estimations for the quality to control the light output.

6 References


