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The Colour Sensor for Regulation of Tunable White Luminaires

***Abstract**. The quality of light is very important factor for human well-being. Except of the light intensity also the correlated colour temperature (CCT) of light is important parameter that influences the mood of people and their performance. The possibility of changing CCT of white light has gradually become a standard part of higher-class lighting installation. The manufacturers have developed various methods of Tunable white control – manual, remote-controlled or controlled via standard wired protocols such as DALI. The more complex control devices even offer possibility of dynamic CCT changing throughout the day according to the circadian cycle (according to the changes in CCT of sunlight). Nevertheless how complex the algorithm of CCT setting is, it can never dynamically react to the changes of ambient light condition unless there is a sensor for feedback measurement. The advantages of automated light intensity control using ambient light sensor are well-known. The aim of this paper is to describe an application of general purpose colour sensor as the feedback element for the regulation of Tunable white luminaires. Firstly, the theoretical basis of CCT measurement is described. Subsequently the paper presents the results of several measurements and case studies. Finally, the last part of the paper is dedicated to the concept of colour sensor that is powered directly from the light it is measuring using energy harvesting methods.*

Keywords: Tunable white, colour sensing, regulation, DALI.

Introduction

The sunlight is the most natural light source for all living being – animals, plants or humans. Therefore also all the artificial light sources are always compared to the sunlight; mainly regarding the spectral quality. However, the light spectrum of the sunlight is not constant throughout the day (Fig. 1). All living beings are sensitive to these changes as they represent a kind of biological clock that tells what time of day it is or what season it is. The invention of artificial light sources has made the people more independent from the daytime. However these biological clocks inside us cannot be simply forgotten. Whatever adaptive the people can be the lack of natural sunlight cycle (so called circadian rhythm) impacts their overall feeling or their health.

Spectral quality of light can be described by several parameters. One of them is correlated colour temperature (CCT). CCT is often used for defining the “colour” or the “tune” of the artificial white light sources.

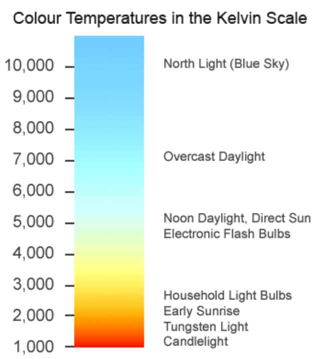


Fig. 1. Examples of various CCTs.

Tunable white concept

The most of the luminaires used in various applications are single-colour. They produce the light of constant CCT. Due to the temperature changes or aging of the light source, the CCT of light can be shifted. However this shift neither is desired nor controllable. By the combination of two or more light sources of different spectrum the one can get the luminaire with controllable CCT of the light. These luminaires are called Tunable white as they offer the possibility to “tune” the colour temperature of the light. There are various methods how the changes of colour temperature can be achieved. The simplest method uses two white light sources with different colour temperatures. The colour temperatures of these light sources define the range of colour temperature tuning. By changing the ratio of brightness of both light sources the resulting colour temperature changes. More advanced method uses three monochromatic light sources – red, green and blue. Using more light sources makes colour temperature setting more precise and also the shape of the spectrum can be more similar to the spectrum of the sunlight, making the resulting light more natural.

Combination of tunable white luminaires and algorithms based on statistics (changes of sunlight throughout the day) can create dynamic sequences that in ideal cases simulate the changes of sunlight. The original statistics data can be adjusted, for example by extending the period with higher colour temperature in order to boost the performance of employees during the work hours. However this is valid only in ideal cases without outer influences. First point is the sunlight itself. The effect of extended cold white period can be totally neglected when there is warm evening sunlight from outside. Also the colours of the objects inside the room or the colour of the walls and floor can change the final colour temperature that can be far from the desired one.

To solve this issue out the regulation circuit has to know the actual conditions inside the area. The sensor is the part that provides feedback information. Light sensors are mainly used for sensing the intensity of light. These sensors are sensitive to the whole visible spectrum thus integrating the energy of light perceived by human eyes. By the combination of the light sensors that are sensitive to the different part of the visible spectrum the one can get a sensor that can evaluate the spectral parameters of light such as colour temperature.

The colorimetry and colour temperature

The colorimetry is the part of physics that deal with colour of light – its definition and description. The colour of light is closely related to the human colour vision. The human eyes contain three types of cone cells – each type is sensitive to different part of visible spectrum (red, green and blue). However each individual has slightly different colour sensation. Therefore the basic definitions in colorimetry were made as statistics results based on standard observer. The basic instruments for colour definition are the colour-matching functions and chromaticity diagram.

The idea of the colour-matching is that a combination of three components – red, green and blue (according to the cone types in the human eye) can create any colour. The colour-matching functions are created from the series of tests when the tested subjects (observers) adjust the intensities of the three primary components to obtain the result colour that matches with the reference monochromatic light source. Measured set of colour-matching functions is mathematically transformed into a new set, where the green-matching function is identical with the human-eye sensitivity function $V(\lambda)$. There are several versions of the colour-matching functions - the mostly used are those of CIE(1931) and CIE(1978). These colour-matching functions are shown in Fig. 2. The colour-matching functions are dimensionless. When applying these function on the power density $P(\lambda)$ of the light the tristimulus values X, Y and Z are obtained.

(1) $$X = \int_\lambda \bar{x}(\lambda)\, P(\lambda)\, d\lambda$$

(2) $$Y = \int_\lambda \bar{y}(\lambda)\, P(\lambda)\, d\lambda$$

(3) $$Z = \int_\lambda \bar{z}(\lambda)\, P(\lambda)\, d\lambda$$

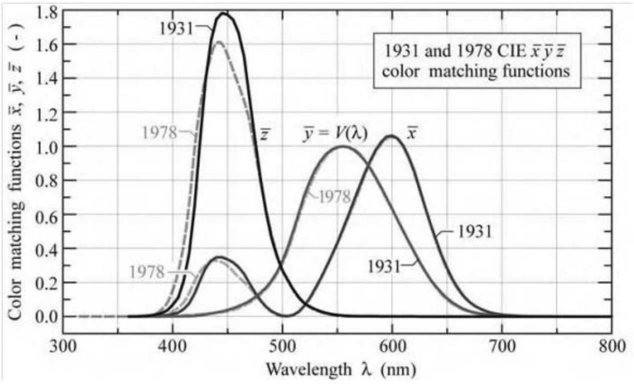


Fig. 2. Colour matching functions according to CIE 1931 and CIE 1978 [1].

The tristimulus values represent the amount of power of each component (red, green and blue) to obtain the light (or the colour of light) with given power density $P(\lambda)$. The values X, Y and Z are used to calculate the coordinates in the chromaticity diagram x and y:

(4) $$x = \frac{X}{X+Y+Z}$$

(5) $$y = \frac{Y}{X+Y+Z}$$

These coordinates represent the stimulation by primary component divided by entire stimulation. Also the value of z can be calculated in the analogue way, but it is considered to be redundant as it does not add any new information. CIE (1931) chromaticity diagram is shown in Fig. 3. The monochromatic colours are located on the perimeter of the diagram, while the white light is located in its centre. The central point of the diagram is called equal-energy point and it represents the light with a constant spectral distribution (X=Y=Z). The term white light is not a strict definition. There are a large number of spectrums and colours that are considered as white. The planckian black-body radiation spectrum has been chosen as a standard for white light source, as it can be described with single parameter (colour temperature).

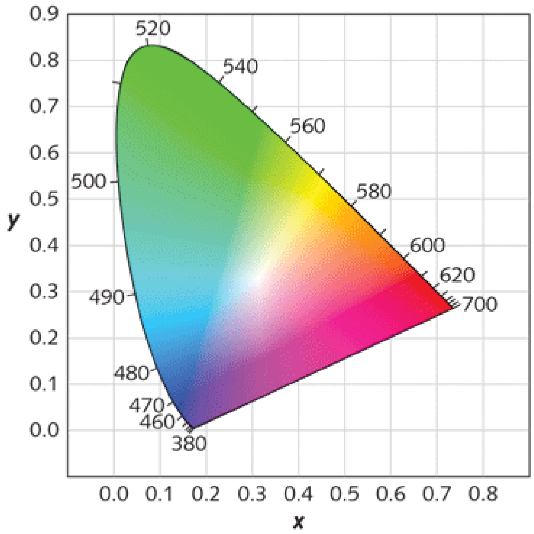


Fig. 3. Chromaticity diagram [1].

It may seem that natural standard for the white light is the sunlight, but as the sunlight contains also great amount of infrared and ultraviolet radiation it is not suitable. The black-body spectrum is defined according to the equation:

(6) $$I(\lambda) = \frac{2.h.c^2}{\lambda^5.\left(e^{\frac{h.c}{\lambda.k.T}}-1\right)}$$

where h in Planck constant and c is the velocity of light in vacuum. The spectrum of the black-body radiation changes with its temperature T. For lower temperatures the most of the radiation is in the longer wavelength, and with increasing of the temperatures it moves to the shorter wavelengths. This temperature is used for characterisation of white light. Colour temperature is the temperature of a planckian black-body radiator that has the same chromaticity location as the white light source considered. Chromaticity points of a planckian black-body radiator at various temperatures create so called planckian black-body locus inside the chromaticity diagram. If the chromaticity point of the white light source is not located directly on the black-body locus correlated colour temperature (CCT) is used. CCT is defined as the colour temperature on black-body locus which is closest to the chromaticity point of the white light source. The meaning of closest depends on the chromaticity diagram used. For uniform chromaticity diagram (coordinates u' and v') it is the colour temperature with the shortest geometrical distance. When using (x,y) chromaticity diagram the CCT is obtained using constant CCT lines [1].

The colour sensor

The most important component of each sensor is the sensing component. If the sensor is chosen properly it can safe much effort in later signal processing stage. For the application of sensor for measuring of colour temperature the colour sensor MTCSiCS by MaZet [2] has been selected. It contains an array of photodiodes that are connected in series. Each branch of photodiodes is sensing the light that is filtered by a different optic filter. Three optic filters have spectral characteristic calibrated according to the tristimulus values defined by CIE(1931). Optic filters ensure that the three output signals are functions of tristimulus values X, Y and Z (Fig. 4).

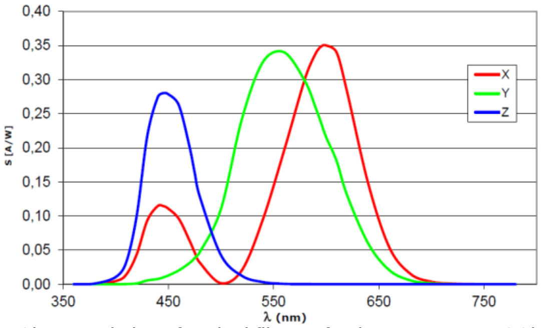
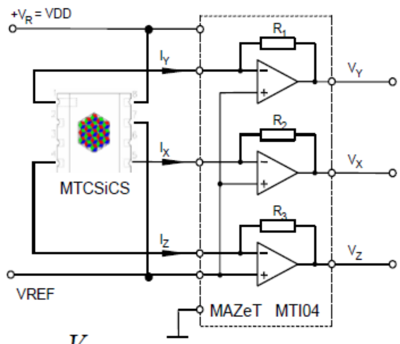


Fig. 4. Characteristics of optical filters of colour sensor MTCSiCS [2].

Output signals are photocurrents therefore it is necessary to transform them into the voltages using operational amplifier connected as trans-admittance amplifier (OTA) or current-to-voltage converter. The feedback resistor defines the gain of the conversion. In combination with analog multiplexer it is possible to switch between various gains (Fig. 5). This allows for precise measurement in extended range of ambient light level. Precise measurement needs also precise and stable voltage reference for biasing the sensor, and also as a reference voltage for analog-to-digital convert (ADC). For practical reasons ADC integrated in the microcontroller unit was used. The resolution of ADC is 12-bit with possibility of oversampling to the 16-bit value. For better precision also the reference voltage is sampled. The OTA used for current conversion into voltage has negative characteristic. It means that output voltage equals to reference voltage when there is small photocurrent, and goes towards zero when the photocurrent is increasing. This negative characteristic is corrected by subtracting the output signal from the reference voltage (the characteristic is inverted). Finalised ambient light sensor is shown in Fig. 6.



$$R_x \approx \frac{V_{Out}}{I_{Photo}}$$

Fig. 5. Connection diagram of the colour sensor [2].

Tristumulus values X, Y and Z have to be corrected according to the correction curves from calibration measurement. Calibration measurement was performed by spectroradiometer that was used as reference – directly with the reference tristimulus values. Each of the tristimulus values has its own correction function (second order polynomial). Corrected tristimulus values are used for colour temperature calculation according to the McCammy's formula [4]:

(7) $$CCT = 449n^3 + 3525n^2 + 6823.3n + 5520.33$$

(8) $$n = \frac{(x-0.332)}{(0.1858-y)}$$

Afterwards calculated colour temperature has to enter the final correction function that results in real CCT in the range of calibration. The calibration has been performed in the range from 20 lx to 20,000 lx, and from 2,700 K to 6,000 K. During the calibration Tunable White LED chip Tiger Zenigata (25 W) by Sharp [3] was used as light source. For ambient lux level measurement tristimulus value Y is calibrated directly in luxes.

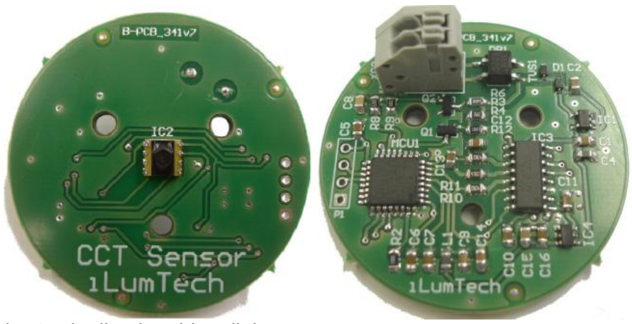


Fig. 6. Finalised ambient light sensor.

The communication with sensor

To read the measured values from the sensor the communication interface has to be implemented. The most commonly used digital interface in lighting industry is DALI bus. DALI stands for Digitally Addressed Lighting Interface. The interface uses two wires. The voltage across the wires is high (12 to 22.5 V) in idle state and low during the communication (-3 to 6 V). The transferred data are encoded using Manchester bi-phase coding with baudrate of 1200 Bd. DALI bus doesn't offer great bandwidth but it is robust and resistant to the interferences. The advantage is that DALI bus can be lead along the power wiring.

DALI bus is mainly used for dimming the luminaires. However, as a standard in lighting industry also the sensor applications have adopted this interface. The main advantage is the direct connection to the luminaires and possibility of their regulation without any device in-between.

Currently there is no official DALI standard (in meaning of standardized commands) for light or colour sensors. It is supposed that the standard can be prepared and released in next 3-4 years. Therefore in our application proprietary extension of DALI commands has been used. The protocol uses so called "extended DALI commands" that are different for each type of DALI device. The commands were created not only for reading the measured values but also in order to allow for the direct regulation of the luminaires. It is possible to set desired values of lux level and colour temperature and both of them can be regulated in parallel.

The regulation of the luminaires

The luminaires to be regulated are selected by their address. The command set offers possibility of single luminaire control or control of the group of luminaires which is more practical. DALI protocol allows for creating up to 16 groups of luminaires. The regulation settings depend on the type of the tunable white luminaire used. Three types of tunable white concepts are supported: first method is based on cold and warm channel with separated addresses, second method is based on brightness and colour temperature channel with separated addresses and the last method is based on brightness and colour temperature channel with single address. The sensor can regulated all three types of TW luminaires in parallel. The last parameter that can be set is the speed of regulation in means of the period between the regulation commands. Because used commands are not standardized the controller for data reading and sensor settings was created as well (Fig. 7).

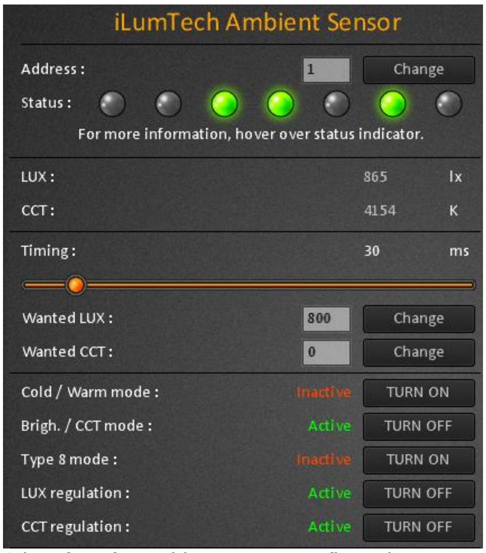


Fig. 7. PC interface for ambient sensor configuration.

The testing measurement

The colour sensor was fitted inside proper housing for the installation in the ceiling. The small mock-up of two separated cells was created (Fig. 8). Two colour sensors were installed, one inside each cell. One of the cells was also equipped with tunable white LED strips powered by DALI controlled LED driver. The sensors and the LED driver were connected to DALI bus. The colour sensor in the cells with LED strips was set in order to regulate the LED strips to keep constant lux level and CCT. The goal was to compare the light conditions in the cell with regulated luminaires and the daylight conditions without artificial lighting. The pre-set value for lux level was 800 lx and for the CCT the value was 3500 K. The regulation mode was set to Brightness/CCT mode. This means that the sensor directly regulated the brightness of the luminaire and its CCT level.

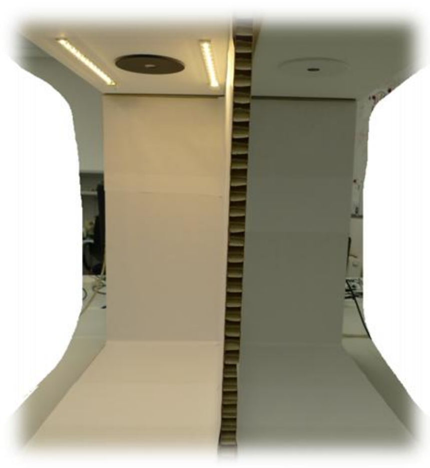


Fig. 8. The mock-up for the measurement.

The test lasted for 60 hours. The weather conditions outside were changeable but it was mostly cloudy. The changeable weather conditions are visible also on the results of the lux level measurement (Fig. 9). It can be seen that the ambient sensor regulated both the lux level and CCT. During the fast changes of the sunlight intensity the regulation was too slow to follow the changes. The next result of the measurement is that parallel regulation of brightness and colour temperature can be hard task – sometimes not possible to complete. Any change of brightness level subsequently influences resulting CCT and vice versa. This is obvious issue when some of the light sources (for example sunlight) cannot be regulated by the sensor. During the day the influence of sunlight was significant – LED strips were not able to compensate it. The results were different during the night when the sunlight is missing. The measured lux level and CCT follows the pre-set values.

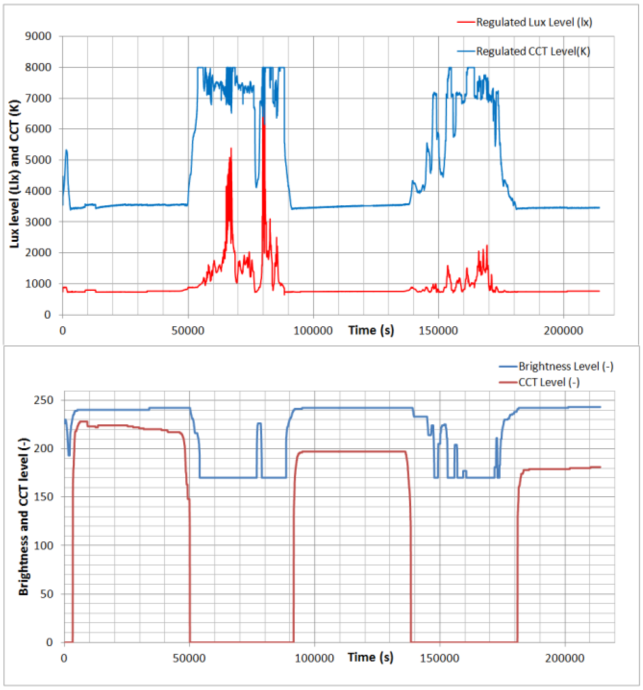


Fig. 9. Results of the testing measurement – upper graph shows the changes of lux level and CCT in the cell with regulated tunable white luminaire, lower graph shows actual brightness and CCT levels of the tunable white luminaire.

The Idea of Self-Powered Sensor

Existing ambient light sensors are usually designed for the installation inside the ceiling. When the sensor is located in the ceiling it can be easily powered as the wires can be hidden. However, the light parameters measured from the ceiling can be different than the light parameters measured directly on the table. The problem is that the ceiling-mounted sensor collects only reflected light whose spectrum is influenced by different colour of the objects under the sensor. Therefore in order to have more precise measurement the sensor should be located directly on the table (or other place where defined light parameters are desired). It is not comfortable to have extra wires on the table to power the sensor and to communicate with it. The sensor should communicate wirelessly and should be powered without additional wiring. The solution can be battery but it needs periodical recharging or replacement.

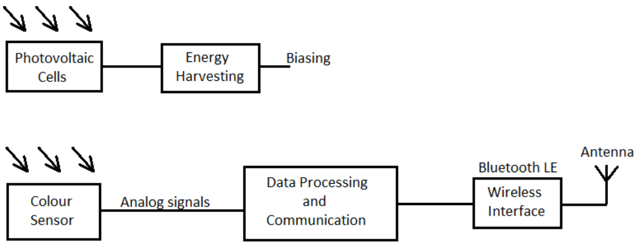


Fig. 10. Block schematic of self-powered ambient light sensor.

But the medium which is sensed by the sensor – light – can be also used for powering the sensor using the photovoltaic cells. The sensor should be reasonably small therefore also the photovoltaic cells must be limited in size. As the light conditions usually change slowly it is enough to measure them only in periods of tens of seconds that offers enough time for biasing circuitry to recover before next measurement (power consumption between the measurements should be lower than 1 μA). Wireless interface has to be also ultra low-power – Bluetooth 4.0 (or Bluetooth Low Energy) fulfils this conditions. The self-powered ambient light sensor block scheme is shown in Fig. 10.

Conclusion

Modern tunable white luminaires in combination with the colour sensors bring new possibilities in customizing ambient light condition according to the user's needs. The CCT of ambient light is important factor that influences moods and feelings of people. The implementation of a colour sensor allows for reading of the actual CCT and subsequent regulation of tunable white luminaires in order to reach desired value of CCT and lux level. The practical implementation of colour sensor was presented using the chip MTCSiCS by MaZet. The output signal of the chip is digitalized and processed. After the calibration measurements the sensor was able to measure absolute values of lux level and CCT. For the communication with the sensor and the regulation of the luminaires DALI bus was chosen as a standard in lighting industry. Special PC application was created for the configuration of the sensor and for reading of measured values. Finalized ambient light sensor was tested in the mock-up with two separate cells. The testing measurement showed that the sensor is regulates the brightness and CCT but their parallel regulation can be difficult as these parameters influence each other. Further testing will follow in order to optimize the performance of the sensor for practical usage in the lighting installations with tunable white luminaires. In the end of the article the idea of self-powered ambient light sensor was presented.

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