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Simulating Sunlight Colour Temperature for the Application of Indoor Lighting

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Abstract: Good lighting quality plays a key role in an interior environment. In order to maintain and comforting environment for the occupants it becomes crucial to maintain appropriate lighting. This study illustrates an LED colour control algorithm which modifies illuminance and colour temperature according to daylight. The combination of six different colours of LEDs, i.e., red, green, blue, amber, lime and white (2200 K) creates white light. It aims to illuminate indoor spaces to mimic daylight. Daylight changes over a range of colour temperatures. The colour mixing algorithm varies the LED luminance ratios and with the combination of both natural light and artificial lights the room is illuminated, thereby, saving the overall energy consumption without compromising quality of light.

Key words: Colour temperature, daylight, illuminance, LED, energy saving, colour mixing algorithm

INTRODUCTION

Good lighting quality plays a key role in an interior environment. In order to maintain and comforting environment for the occupants it becomes crucial to maintain appropriate lighting. Over the years commercial spaces such as offices, railway stations, hospitals, public areas, healthcare facilities and factories have been using incandescent and fluorescent light fixtures to light different areas such as hallways, waiting rooms, bathrooms, patient rooms, offices, etc. These lights have been the go-to because of their cost, availability and output. What facility managers not succeed to realize is that incandescent and fluorescent lights aren't dependable and can have many negative effects on the occupants. Moreover, LED light bulbs and fixtures are the best alternatives, for many reasons when it comes to lighting in hospitals.

Over the centuries, humans have been living outdoors and have grown to the requirement of exposure to sunlight for well being and health benefits. With the introduction of architecture, we have continuously pursued to let in day lighting by means of windows and skylits because of its large number of benefits. And similarly today also while constructing any residential building, commercial building or office space, we tend to increase the daylight coming into the rooms and the work plane area.

This study aims to illuminate indoor spaces by varying the intensity of six LEDs that is red, green blue, amber, lime and white to mimic daylight. Daylight changes over a range of color temperatures varying from 3000 K at 7 am to 7500 K at 4 pm. The color mixing algorithm varies the LED luminance ratios and with the combination of both natural light and artificial lights the room is illuminated according to IS 3646 Standards.

MATERIALS AND METHODS

Daylight has a number of benefits on the health of the people and it has been an main area of research over the past a number of years now. At the same time vision also, plays an important role. Moreover, the area of link between daylight and health is still being researched upon through a various number of experiments and studies. The Light Emitting Diode (LED) technology has a vast application area ranging from signal lighting, street lighting, vehicle lighting, architecture and indoor lighting. While designing a lighting system certain key points should be considered like visual task requirements, visual environmental requirements, CRI, quality of lighting, type of luminaire, its luminous efficacy, orientation and placement of the luminaire, room dimensions, reflectance of the walls and application of the room plays an important role.

At the same time it should also have a uniform illuminance pattern and comfortable color characteristics

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reducing the glare as well. In case of insufficient light or unsuitable lighting conditions it may also, cause several disorders both in the short as well as long-term.

The daylight or natural light comprises of atmospheric light and direct sunlight that is the Sun radiation dispersed by dust and water. Designs for utilizing LED lighting and hybrid sunlight illumination have been proposed by Tsuei *et al*. (2010) which suggests that to eventually provide the even illumination pattern, LED light and the sunlight can be mixed by a light box design and henceforth, the problem of color mixing can also be determined by adjusting and changing the ratio of RGB LEDs which is inside the light box (Tsuei and Sun, 2009). The reflector used in a combination of lamp luminaire plays a vital role in controlling the illumination. It is also, found that by diffuser can be used in order to decay the glare. Simultaneously, illuminance becomes more uniform. It is one of the best and the most advantageous way to avoid glare (Tsuei *et al*., 2008).

By Tsuei and Sun (2011) the researcher has proposed to copy the sunlight like color hue, temperature and brightness with RGB LEDs for the application of indoor lighting by simulating the tristimulus values and thereby by using a conversion algorithm convert it into the corresponding RGB ratios to control the LEDs. Similarly by Kim, Hoon *et al*. the researcher suggests a control system which uses color control algorithm that adjusts the illuminance and color temperature independently. The color temperature range varies from 3500-7500 K and illuminance from 500-1500 lux. Moreover, Buso and Spiazzi (2011) the researcher designs a lamp which presents a controlled strategy for both luminance and color temperature. The luminaire design is done using green, a cool white light source and red. By PWM dimming the luminance of each LED array, the regulation of intensity and color temperature can be obtained by independently adjusting it Lohaus *et al*. (2013). By Zhu *et al*. (2017), the researcher proposes a color control algorithm performed by a digital controller which works on the principle of PWM dimming.

The proposed lighting system uses a six LED system with a combination of red, green, blue, amber, lime and white (2200 K). Through this various colours can be generated. Figure 1 shows the flow of the complete algorithm starting from finding the color coordinates based on the CCT. With the use of photo sensor the average lux levels are found out and accordingly the PWM technique is used. The ratio of LED light intensity, determine the mixed colour. This ratio can also be linearly controlled through PWM dimming technique. The proposed colour control algorithm is performed by a digital controller. It is explained in the coming section, according to a known input vector [x_m, y_m, I_m] and four independent PWM dimming duties is created to attain desired illuminance and colour temperature.

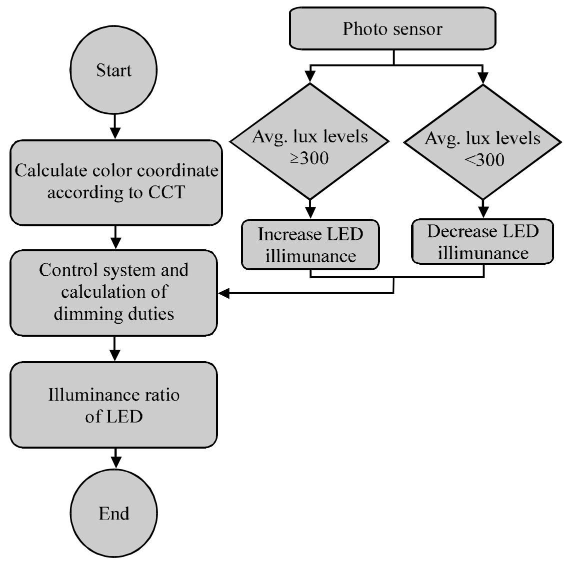

Fig. 1: Flowchart of the implemented LED lighting control

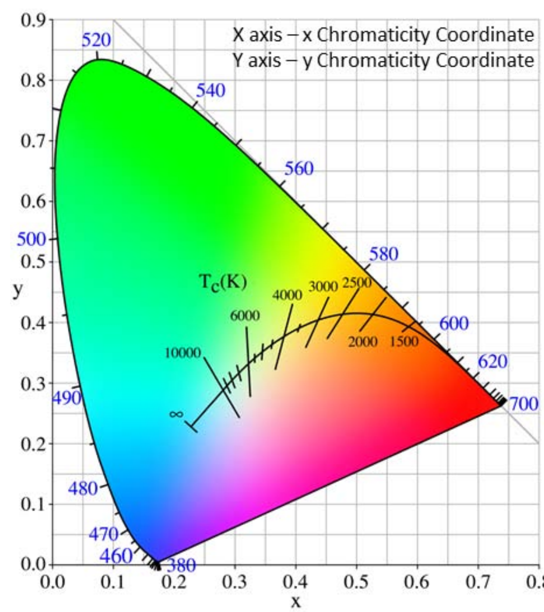

Fig. 2: CIE 1931 chromaticity diagram

In 1931, Commission Internationale de l'Eclairage (CIE) defined that human eye has different types of colour sensitive cones. The colour can be expressed by their weighted summation, called the tristimulus values. The chromaticity coordinates of any color can be found out through CIE 1931 chromaticity diagram is as shown in Fig. 2.

Colour mixing algorithm: Our eyes consist of different types of colour sensitive cones to perceive and sense different forms of light, defined by Commission Intemationale de l'Eclairage (CIE) in 1931 first. The colours can be conveyed by their weighted summation, called the tristimulus values. Any colour can be defined illuminance I_m. From x and y, the two colour coordinates on the chromaticity diagram and from the coordinate value, the colour temperature can be obtained.

In order to manage the colour temperature and illuminance of the proposed LED, a relationship between each colour of LED the mixed colour have to be determined. The chromaticity coordinate of the mixed light is found out with the help of colour mixing algorithm which is a weighted linear combination of each chromaticity coordinates. Thus with the help of chroma meter the colour coordinates of the red, blue, green amber, white and lime, LED module can be obtained by calculating the following Eq. 1 and 2:

$$x_m = \frac{\frac{x_R I_r}{y_R} + \frac{x_G I_g}{y_G} + \frac{x_B I_b}{y_B} + \frac{x_A I_a}{y_A} + \frac{x_L I_l}{y_L} + \frac{x_W I_w}{y_W}}{\frac{I_r}{y_R} + \frac{I_g}{y_G} + \frac{I_b}{y_B} + \frac{I_a}{y_A} + \frac{I_l}{y_L} + \frac{I_w}{y_W}} \quad (1)$$

$$y_m = \frac{\frac{y_R I_r}{y_R} + \frac{y_G I_g}{y_G} + \frac{y_B I_b}{y_B} + \frac{y_A I_a}{y_A} + \frac{y_L I_l}{y_L} + \frac{y_W I_w}{y_W}}{\frac{I_r}{y_R} + \frac{I_g}{y_G} + \frac{I_b}{y_B} + \frac{I_a}{y_A} + \frac{I_l}{y_L} + \frac{I_w}{y_W}} \quad (2)$$

where, constants x_R, y_R, x_G, y_G, x_B, y_B, x_A, y_A, x_L, y_L, x_w and y_w are the color coordinates of each color LEDs and I_r, I_g, I_b, I_a, I_l and I_w are the required illuminances of each LED to generate the required color of light.

The illuminance of mixed color I_m follows the linear addition principle, i.e., $I_M = I_R+I_G+I_B+I_A+I_L+I_W$. Therefore, the system matrix Eq. 3 of RGBALW LED module is expressed as follows:

$$\begin{bmatrix} 0 \\ 0 \\ I_M \end{bmatrix} = \begin{bmatrix} \frac{X_R - Y_M}{Y_R} & \frac{X_G - Y_M}{Y_G} & \frac{X_B - Y_M}{Y_B} \\ \frac{X_A - Y_M}{Y_A} & \frac{X_L - Y_M}{Y_L} & \frac{X_W - Y_M}{Y_M} \\ \frac{Y_R - Y_M}{Y_R} & \frac{Y_G - Y_M}{Y_G} & \frac{Y_B - Y_M}{Y_B} \\ 1 & 1 & 1 \\ \frac{Y_A - Y_M}{Y_A} & \frac{Y_L - Y_M}{Y_L} & \frac{Y_W - Y_M}{Y_M} \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} I_R \\ I_G \\ I_B \\ I_A \\ I_L \\ I_W \end{bmatrix} \quad (3)$$

$$A = \begin{bmatrix} \frac{X_R - Y_M}{Y_R} & \frac{X_G - Y_M}{Y_G} & \frac{X_B - Y_M}{Y_B} & \frac{X_A - Y_M}{Y_A} \\ \frac{X_L - Y_M}{Y_L} & \frac{X_W - Y_M}{Y_M} & & \\ \frac{Y_R - Y_M}{Y_R} & \frac{Y_G - Y_M}{Y_G} & \frac{Y_B - Y_M}{Y_B} & \frac{Y_A - Y_M}{Y_A} \\ 1 & 1 & 1 & 1 \\ \frac{Y_L - Y_M}{Y_L} & \frac{Y_W - Y_M}{Y_M} & & \\ 1 & 1 & & \end{bmatrix} \quad (4)$$

$$B = \begin{bmatrix} 0 \\ 0 \\ I_M \end{bmatrix} \quad (5)$$

$$I = \begin{bmatrix} I_R \\ I_G \\ I_B \\ I_A \\ I_L \\ I_W \end{bmatrix} \quad (6)$$

Then, (Eq. 3) can be simplified as:

$$B = A.I \quad (7)$$

where, the total illuminance of the LED module is represented as B, the coordinate relationships among the mixed color and the color of each LED is represented as A and illuminances of each LED are represented as I. The illuminance matrix I can be found, if inverse matrix of A exists, then it can be obtained by the following Eq. 8:

$$I = A^{-1}.B \quad (8)$$

where, A^{-1} can be calculated using MATLAB with the help of pseudo inverse function. As an outcome, I becomes a function of x_m, y_m and I_m. The illuminances of each LED can be determined, if the illuminance and mixed color coordinate are given:

$$\begin{bmatrix} I_R \\ I_G \\ I_B \\ I_A \\ I_L \\ I_W \end{bmatrix} = \begin{bmatrix} \frac{X_R - Y_M}{Y_R} & \frac{X_G - Y_M}{Y_G} & \frac{X_B - Y_M}{Y_B} \\ \frac{X_A - Y_M}{Y_A} & \frac{X_L - Y_M}{Y_L} & \frac{X_W - Y_M}{Y_M} \\ \frac{Y_R - Y_M}{Y_R} & \frac{Y_G - Y_M}{Y_G} & \frac{Y_B - Y_M}{Y_B} \\ 1 & 1 & 1 \\ \frac{Y_A - Y_M}{Y_A} & \frac{Y_L - Y_M}{Y_L} & \frac{Y_W - Y_M}{Y_M} \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ I_M \end{bmatrix} \quad (9)$$

Table 1: Chromaticity coordinates of all the colors

Colors	X	Y
Red	0.7002	0.2993
Green	0.2167	0.7132
Blue	0.1141	0.1185
Amber	0.6159	0.3831
Lime	0.4082	0.5254
White	0.4332	0.4024

Table 2: Variation of CCT during the day and the corresponding x and y chromaticity coordinates

Time	CCT	x_m	y_m
7 am	3000	0.4541	0.4407
10 am	5000	0.3458	0.3829
12 pm	6500	0.3046	0.3866
4 pm	7500	0.2932	0.3352

Table 3: Specifications of the LEDs of different colors

Colors	Lumen output (minimum)	Lumen output (typical)
Red	35	49
Green	90	115
Blue	25	41
Amber	20	30
Lime	125	135
White (220K)	70	85

Table 4: Quantity of single LEDs required for each color

Colors	7 am	10 am	12 pm	4 pm
Red	105	35	35	35
Green	230	230	345	345
Blue	25	100	75	75
Amber	120	100	120	120
Lime	270	270	135	135
White	170	170	170	85
CRI	87.4	80.2	85.7	85.1

The chromaticity coordinates of all the colors red, green blue, amber, lime and white (2200 K) can be seen in Table 1.

LED design: The sunlight color temperature varies from morning to evening ranging from 3000 K at 7 am to 7500 K at 4 pm. Using Konica Minolta CL-200 chroma meter the color coordinates of sunlight at different times can be calculated. Further using the color mixing algorithm from the previous section we can calculate the ratios of RGBALW LEDs at different CCTs. Table 2 shows the variation of CCT during the day and the corresponding x and y chromaticity coordinates.

The specifications of the LEDs of different colors selected for the design are mentioned in Table 3. Now using the color mixing algorithm, we calculate the ratios for different colors and calculate the number of LEDs required. Table 4 shows the quantity of single LEDs required for each color required to get the specific CCT and CRI above 80.

All the LEDs selected operate at 350 mA with a common driver circuit. With help of test research luminaire with all 6 color LEDs using a goniophotometer

Table 5: Photometric data of the lamp at various color and temperatures

θ	E 5000 K	6500 K	7500 K
0	324.00	341.00	352.00
5	321.00	339.00	349.00
10	316.00	333.00	343.00
15	308.00	325.00	334.00
20	297.00	313.00	322.00
25	282.00	297.00	305.00
30	263.00	277.00	285.00
35	241.20	254.00	262.00
40	218.50	229.60	235.90
45	193.30	203.00	208.50
50	166.40	175.10	180.40
55	142.50	149.30	154.30
60	115.70	122.30	125.50
65	90.70	96.00	99.10
70	67.40	71.20	73.40
75	45.70	48.00	48.90
80	27.20	27.80	28.60
85	12.14	12.27	13.12
90	2.83	3.22	3.24

Table 6: Average illuminance only due to sunlight in the room at different period

Time	Manual readings	Overcast sky	Avg. sky	Clear sky
8 am	140	167	377	319
10 am	354	264	628	608
12 pm	238	296	606	802
2 pm	237	255	616	569
4 pm	94	119	321	308

photometric experiments are performed to get the illuminance of light at different angles. Table 5 shows the photometric data of the lamp at different color temperatures. Using the goniophotometer data from Table 5 IES files for all the three different types is prepared. These act as luminaire files for importing in DIALux Software.

Room planning: A room is selected for the simulation in DIAlux using the above mentioned luminaire files. The seminar hall has 10 windows through which sunlight can enter. At different times of the day according to the movement of Sun effect of daylight in the room varies. Table 6 shows average illuminance only due to sunlight in the room at different period.

It can be seen that during avg. sky and clear sky conditions the average lux levels are beyond the required lux levels that is 300 lux as per IS 3646 standards. Only during overcast sky conditions the average lux levels are under 300 lux (Fig. 3).

Existing system: The existing lighting design of the Seminar Hall consists of a combination of FTLs and CFLs. Table 7 shows the specifications of the existing lighting system.

The average lux levels using the above combination and quantity of lamps is found out to be 591 lux which is way above the IS 3646 Standards.

Fig. 3: DIALux simulation result for Department Seminar Hall

Table 7: Specifications of the existing lighting system

Lamp types	Qty.	Power (W)	Operating (h/month)	Energy consumed/ month (kWh)
Recessed modular FTL	16	67	86	92.192
CFL	15	26	86	33.540
Total				125.732

RESULTS AND DISCUSSION

In this study, a color mixing algorithm for six colors has been proposed. Using the target chromaticity coordinates ratios for different LED color luminance is found out.

Proposed system: The proposed system uses the LED luminaire developed above. The new system consists of 3 red, 3 green, 4 blue, 6 amber, 2 lime and 2 white LEDs. The room requires 32 LED luminaires to meet 300 lux as per IS 3646. Artificial lights alone can provide 310 lux. Using the combination of both daylight and new lighting system the room is illuminated. Table 8 shows the contribution of natural lighting and day lighting for illuminating the room for overcast sky.

By using a combination of both natural lighting and artificial lighting, we can decrease the energy consumption of any building. Through the above simulations it can be seen that during the day time the LED luminaire should operate only at half of their maximum intensity and this saves energy consumption. Moreover, when daylight is not available these luminaires can be controlled accordingly and using the color mixing algorithm these can mimic the day light in indoor environment. The power and energy analysis of the new system is as shown in Table 9.

With the new proposed system target illuminance of 300 lux is met as well as the uniformity of light is also increased to 0.66. The new system reduces the overall power consumption by 68% and that can be further reduced while incorporating day lighting.

Table 8: Contribution of natural lighting and day lighting

Time of the day	Natural lighting	Artificial lighting illuminance (lux)	Average illuminance (lux)
10 am	268	37.2 (12%)	305
12 pm	300	0 (0%)	300
4 pm	154	155 (50%)	309

Table 9: Power and energy analysis of the new system

Lamp types	Qty.	Power (W)	Operating (h/month)	Energy consumed/ month (kWh)
Proposed LED luminaire (100%)	32	14.8	86	40.729
Total				40.729

This study uses a type of luminaire which consists of 6 different LED color lights and can be used together to produce white light. At the same time by color control algorithm and PWM dimming the different CCTs to mimic sunlight like color temperature at different times can be produced.

This 6 LED configuration can be used for the application of mood lighting for various areas such as households, gardens and classrooms. The ambience of rooms can also be changed at different times of the day. The other benefits of mood lighting include, reducing the amount of energy consumed and thus amount to be paid for the electricity bill will reduce. By dimming the lights and reducing the amount of energy being used a quiet and subtle atmosphere can be created when the evenings get dark earlier, especially, in the Winter months and thus, saving a substantial amount of money.

Despite of the increased occurrence of automated work processes, the human eye is still superior in spotting flaws and irregularities on product surfaces. Quality inspections depend on the right lighting conditions. The general illumination of factory buildings is often not enough to determine the quality of goods that are to be inspected. The lighting therefore, needs to be tailored according to the products being inspected on the basis of their surface structure, colour, reflections, size and the time taken to inspect them. In these areas CRI play a vital role in determining the actual color of the materials. Also in commercial warehouse operations or shipping yards where laborers need to see markings on shipping containers, light sources with high CRI values is required.

CONCLUSION

This study presents the color mixing algorithm to control the color temperature of a LED luminaire to mimic day light using 6 LEDs that is red, green blue, amber, lime and white. Using lumileds spectrum mixer results can be verified. Also, a test research luminaire with similar characteristics is built and is used to verify the results. Following that the luminaire is used in DIALux to simulate a room with a combination of both natural light and artificial light. It can be conferred that by using a combination of both the energy consumption is low and by varying CCT the sunlight like light can be produced at different period of the day.

SIGNIFICANCE STATEMENT

The color mixing algorithm to control the color temperature of a LED luminaire using 6 LEDs that is red, green blue, amber, lime and white helps to mimic day light and gives the lux level ratios of different colors to get the specific color temperature. The use 6 color LEDs gives a high CRI which plays a vital role in determining the actual color of the material.

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REFERENCES

Buso, S. and G. Spiazzi, 2011. White light solid state lamp with luminance and color temperature control. Proceedings of the International Conference on XI Brazilian Power Electronics, September 11-15, 2011, IEEE, Praiamar, Brazil, ISBN:978-1-4577-1644-7, pp: 837-843.

Lohaus, L., E. Leicht, S. Dietrich, R. Wunderlich and S. Heinen, 2013. Advanced color control for multicolor LED illumination systems with parametric optimization. Proceedings of the IECON 2013 39th Annual Conference on IEEE Industrial Electronics Society, November 10-13, 2013, IEEE, Vienna, Austria, ISBN:978-1-4799-0224-8, pp: 3305-3310.

Tsuei, C.H. and W.S. Sun, 2009. Simulating the illuminance and efficiency of sunlight/led hybrid illuminating system used in indoor lighting design. Proceedings of the 2009 International Symposium on Photonics and Optoelectronics, August 14-16, 2009, IEEE, Wuhan, China, ISBN:978-1-4244-4412-0, pp: 1-4.

Tsuei, C.H. and W.S. Sun, 2011. Momentary adjustment means for simulating the sunlight color temperature, hues and brightness with RGB LEDs in indoor lighting. Phys. Procedia, 19: 239-243.

Tsuei, C.H., J.W. Pen and W.S. Sun, 2008. Simulating the illuminance and the efficiency of the LED and fluorescent lights used in indoor lighting design. Opt. Express, 16: 18692-18701.

Tsuei, C.H., W.S. Sun and C.C. Kuo, 2010. Hybrid sunlight/LED illumination and renewable solar energy saving concepts for indoor lighting. Opt. Express, 18: A640-A653.

Zhu, Z.M., X. Sun and B. Peng, 2017. Rectangular illumination based on diffuse reflective off-axis surface. IEEE. Photonics J., 9: 1-8.