Adjustable lighting system based on circadian rhythm for human comfort

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Abstract The artificial lighting condition in which humans are exposed have been proven as a harmful factor on their well-being, which is regulated mainly by circadian rhythm. Especially since the COVID-19 pandemic, where external factors forced the society to adapt into new standards when it comes to their jobs and regular activities, lockdowns and work-from-home made most people start spending a portion of their life exposed to artificial sources of light. Technological advances have made lights more efficient and improved their intensity. Light-emitting diodes (LEDs), for example, generally produce high-intensity bluish tone light, which may affect the circadian rhythm. However, it is possible to create lighting systems able to vary the intensity and correlated color temperature (CCT) of the lighting. This work proposes a lighting system that allows adjusting the intensity and CCT of light via remote control on a smartphone application synchronized with time, following a pattern that aims avoid the undesirable artificial lighting effects on circadian rhythm. Using two LED arrays containing 10 LEDs each, suitable results were reached, presenting maximum difference of 3.35 % for CCT and 5.57 % for luminous flux in comparison with reference values.

Keywords Circadian rhythm · Light-emitting diodes · Lighting · Lighting control · System integration

Introduction

Lighting affects the emotional and biological state of the human body. The change in the color temperature and illuminance in an ambient can affect not only the emotional side, but the performance at work, learning, disposition and the various tasks performed in ambient where natural light is not available [1–3]. This occurs because the light receptors in the human eye control the circadian rhythm, a biological system that, through the perception of light, inform the brain that regulates the hormonal system of the human body [4–6].

In addition, the CCT variation influences not only comfort but also people’s health. Blue wavelengths, which are beneficial during the day for increasing attention, activity, reaction times and mood, are more harmful at night [7]. As shown in Fig. 1, in accordance with an increase in CCT, the ability to perform tasks is improved while the relaxation sensation is decreased. Such effects are controlled by two hormones, serotonin and melatonin, which vary during the day influenced by the light color and intensity [8].

Any type of light at night can suppress the secretion of melatonin, a hormone that at low levels may be associated with the cause of some cancers; however, the light in the blue spectrum is even more damaging in that regard [7, 9].

Recent events regarding the COVID-19 pandemic made hundreds of millions of people suddenly live through lockdowns, in which many have made the abrupt shift to working from home and spending most of their time exposed to artificial light sources; therefore, improvements in order to provide comfort and healthiness through lighting are valuable.

Technological advances in lighting systems have made lights not only more efficient, but also with much greater luminous intensity. For example, LEDs, in addition to being more energy efficient than fluorescent and incandescent bulbs, have a long reliability and lifetime. However,
the common LEDs adopted in lighting produce light with bluish tones and high CCT, which can be detrimental to the comfort and health of people [9, 10].

Several initiatives have been made to understand the effects of light in circadian rhythm and create lighting systems able to improve the human well-being. In [11] was proposed biological clock designed to help adapt to sleepiness to alertness in a 24-hour period. A tunable LED lighting with five color channels for high circadian and visual performances was suggested in [12]. An LED-based system able to smoothly change CCT and the spectral power density (SPD) in region of 460-480 nm was addressed by [13]; the system can be used to control several lamps connected together. Additionally, in [14] a red–green–blue–white LED color-mixing solution was used to mimic both visual and circadian characteristics of the measured dynamic daylight for both sunny and cloudy weather conditions. An LED lighting system capable of reproducing daylight’s changes in relative spectral power and circadian content with time-of-day was reported by [15]; such system is formed by four LED channels with different colors.

All of aforementioned works have advantages; however, some of them were developed, for example, only to provide a warning to the user about the daytime based on light color changing [11] and are complex requiring five different types of LEDs [12] or an increase in the number of control channels [14]. Besides, some works need an adjustment in a specific SPD region to reach the desired result, requiring a complex control algorithm [13] or additional sensors to provide a reference to color [15]. In this way, a lighting system with simple control algorithm and a conception able to compensate the effects of current and temperature in LEDs performance are desirable.

This paper proposes a system that makes it possible to adjust the CCT and adjust the light of an ambient by combining the light produced by two LED arrays containing 20 LEDs (10 warm white and 10 cool white), which are controlled only by two channels. In order to provide the reference current of LED is presented a mathematical model that considers the color-photo-electro-thermal aspects of LED performance together, resulting in an equation that represents the required mixing of color in function of the forward current. The model is programmed into a microcontroller (MCU) algorithm that controls all the system. Additionally, the system uses the concept of Internet of things (IoT) that allows the creation of a smartphone-adjustable lighting system that regulates itself based on the circadian rhythm and time synchronization, aiming for achieving human comfort and well-being through the CCT and light intensity adjustments.

The paper is organized as follows: Sect. 2 presents the entire proposed system; Sect. 3 shows the system design procedure and how the implementation of each sub-system was made. Section 4 presents the experimental results and comments, and Sect. 5 highlights the main contributions of paper and conclusions about them.

**Proposed system**

The proposed system, shown in Fig. 2, is composed of a mobile interface and communication, which provide the user the possibility of personalization or automation in light color and intensity. Through the smartphone, the user can remotely adjust the CCT and luminous flux of the LEDs. It is used in Wi-Fi communication to obtain time synchronization and data transfer to MCU. An algorithm for CCT and luminous flux determination is programmed in the microcontroller; the algorithm contains a mathematical model that provides the reference current able to synthetize the required color and intensity. Finally, the MCU acts to control the system, through a feedback, it is responsible to guarantee that LED receives the adequate current and is equal to reference current, provided by the algorithm, in order to provide high color fidelity and light intensity.

In the next sections will be performed a description of the proposed system, detailing each part of them.

**Design procedure and implementation**

The proposed system is divided into: (a) mobile interface and communication; (b) algorithm for CCT and luminous flux determination; (c) driving LEDs; and (d) control system. Each sub-system is presented in detail as follows:

**Mobile interface and communication**

The communication between mobile app and ESP-32 MCU is done through Wi-Fi. The MCU is programmed upon every initialization to try and connect itself with the Wi-Fi credentials saved on its memory. In the case that the connection cannot be established, the microcontroller will switch itself
into access point mode and create its own Wi-Fi network, where it will wait for a smartphone with the required software to connect.

Upon initialization, the app will try to identify the TCP server established by the microcontroller on the connected network. If it succeeds, it will periodically send data containing the CCT, luminous flux, time of day, and the mode of operation identifier.

In the mobile application, there are two operation modes, manual and automated, the former being user-controlled settings and the latter having predefined values for CCT and luminous flux based on time of day, following a pattern as shown in Fig. 3. This pattern was originated of studies of human circadian rhythms performed by [16–18], where rules were proposed to guide lighting designers to design for circadian stimulus. In Fig. 3, it is observed that the CCT and light intensity are more adequate for each period of time during the day. This CCT and light intensity schedule is programmed in the MCU, and jointly with the algorithm, explained in sequency, they provide the reference current to drive the LEDs.

The user interface consists of two different screens, one for manual mode and other for automatic mode, as shown in Fig. 4. The first one houses the manual controls, having two sliders representing the values for both CCT and luminous flux, as well as a button for sending new network credentials, as per Fig. 4a.

The second screen houses a digital clock and a button for activating the automatic mode of operation, as per Fig. 4b. Both screens show an always present help button as well.

The application was developed in order to send data to the MCU to calculate the reference current that supplies the LEDs. Figure 5 presents a flowchart containing most of the behavioral sequences present on the mobile application.
are used, defined by (2) and (3), respectively. The variation of junction temperature is implicit in the equation with the variation of direct current, as shown in (4).

The \( \Phi(I_f) \) is calculated based on (2):

\[
\Phi(I_f) = \left( n \cdot \Phi_o \cdot (d_0 + d_1 \cdot I_f) \cdot (c_0 + c_1 \cdot T_j(I_f)) \right) 
\]

(2)

where \( n \) is the number of LEDs, \( \Phi_o \) is the rated luminous flux, \( d_0 \) and \( d_1 \) are coefficients of luminous flux versus forward current, \( c_0 \) and \( c_1 \) are coefficients of luminous flux versus junction temperature and \( T_j \) is the junction temperature, all extracted from LED datasheet.

Individually, the CCT of each type of LED is calculated using (3):

\[
CCT(I_f) = \left( e_0 + e_1 \cdot (y_0 \cdot (b_0 + b_1 \cdot I_f)) \cdot (a_0 + a_1 \cdot T_j(I_f)) \right) 
\]

(3)

where \( e_0 \) and \( e_1 \) are chromaticity coefficients of CCT, \( y_0 \) is the rated chromaticity coordinate, \( b_0 \) and \( b_1 \) are coefficients of chromaticity versus forward current, and \( a_0 \) and \( a_1 \) are variation chromaticity coefficients with the temperature.

The temperature is calculated based on the thermal path where the LEDs are assembled, through (4), where \( T_a \) is the ambient temperature, \( R_c q \) is the thermal resistance of assembly (heat sink, insulation, etc.), \( V_f \) is the LED forward voltage, and \( k_h \) is the portion of electrical power that turns into heat.

\[
T_j(I_f) = T_a + R_c q + I_f \cdot V_f(I_f) \cdot k_h 
\]

(4)

The forward current is defined by multiplying duty cycle (D) with the peak forward current \((I_p k)\).

Equations (1-4) are codependent and represent the interrelationships that occur among color-photon-electro-thermal domains in the LED operation.

The diagram in Fig. 6 shows how the data extraction is made from datasheet and how it is processed to find the main equation \( \text{CCT}_{\text{mix}}(I_f) \) [19].

The implementation was made with two LED arrays that use distinct Cree J Series 3030 LEDs. One of them has CCT of 2700K (JK3030AWT-00-0000-000B0HK227E) and the other 6500K (JK3030AWT-00-0000-000B0HL265E). Table 1 shows all coefficients and values extracted from the LED datasheet and used in the mathematical model. These LEDs were chosen because they have all the necessary information to find the parameters in their datasheet to satisfy the \( \text{CCT}_{\text{mix}} \) and parameters shown in Fig. 6.

From the pattern of Fig. 3, with time synchronization, and the model of equation (1) the algorithm is able to generate the reference forward current using duty cycle to provide accurate color and intensity for circadian rhythm.
Fig. 5 Mobile application flowchart

- Start
- Open pop-up with instructions for use
- Was the microcontroller server identified on the Wi-Fi network?
  - YES: Load manual adjustment screen
  - NO: Load "disconnected" screen
- Periodically send configuration parameters (flux, color temp., time, op. mode)

- User clicked the help button
  - Open pop-up with instructions for use
- User interacted with the top bar
  - Load the selected screen
- User clicked the Send new Wi-Fi credentials button
  - Open pop-up with submission form
  - User typed new information and clicked on send
  - Send data to microcontroller
- User clicked on the automatic mode button
  - Inversion of the state of the corresponding variable
Fig. 6 Diagram for CCT and luminous flux determination from LED datasheet [19]

Table 1 LED parameters extracted from datasheet and used in algorithm [26]

| Parameter (symbol) [unit] | LED6500K | LED2700K |
|--------------------------|----------|----------|
| Correlated color temperature (CCT) [K] | 6500 | 2700 |
| Threshold voltage \( (V_{0}) \) [V] | 5.2863 | 5.2863 |
| LED series resistance \( (R_{s}) \) [Ω] | 4.7246 | 4.7246 |
| Voltage drop with temperature coefficient \( (k_{v}) \) [V/°C] | −0.0018 | −0.0018 |
| Reference temperature \( (T_{0}) \) [°C] | 25 | 25 |
| Rated forward current \( (I_{0}) \) [A] | 0.15 | 0.15 |
| Portion of electrical power that turns into heat \( (k_{b}) \) [p.u] | 0.75 | 0.75 |
| Junction to case thermal resistance \( (R_{jc}) \) [°C/W] | 11 | 11 |
| Board to heat sinks thermal resistance \( (R_{pa}) \) [°C/W] | 0.625 | 0.625 |
| Insulation thermal resistance \( (R_{at}) \) [°C/W] | 0.1645 | 0.1645 |
| Heat sink thermal resistance \( (R_{hs}) \) [°C/W] | 2.92 | 2.92 |
| Linear coefficient of luminous flux in function of forward current \( (d_{0}) \) [DN] | 0 | 0 |
| Angular coefficient of luminous flux in function of forward current \( (d_{1}) \) [DN] | 6.65 | 6.65 |
| Linear coefficient of luminous flux in function of junction temperature \( (c_{0}) \) [DN] | 1.064 | 1.064 |
| Angular coefficient of luminous flux in function of junction temperature \( (c_{1}) \) [DN] | −0.002 | −0.002 |
| Rated luminous flux \( (\Phi_{o}) \) [lm] | 124 | 112 |
| Rated forward current \( (I_{0}) \) [A] | 0.15 | 0.15 |
| Linear coefficient of chromaticity coordinate \( y \) in function of case temperature \( (a_{0}) \) [DN] | −0.0002 | −0.0002 |
| Angular coefficient of chromaticity coordinate \( y \) in function of case temperature \( (a_{1}) \) [DN] | 1.0148 | 1.0153 |
| Linear coefficient of chromaticity coordinate \( y \) in function of forward current \( (b_{0}) \) [DN] | −0.097 | −0.097 |
| Angular coefficient of chromaticity coordinate \( y \) in function of forward current \( (b_{1}) \) [DN] | −0.1237 | 1.0148 |
| Central value of chromaticity coordinate \( y \) \( (y_{0}) \) [DN] | 0.3214 | 0.4101 |
| Linear coefficient of CCT in function of chromaticity coordinate \( y \) \( (e_{0}) \) [DN] | 18582 | 3182.2 |

*DN* Dimensionless
Driving LEDs

The LED driving is made by an electronic circuit able to supply the required current to synthesize desired CCT and luminous flux. This circuit applies current with PWM to LEDs. Among the several methods to control LEDs, the most widespread are amplitude modulation (AM), PWM, and bi-level modulation (BLM) [20]. AM is the simplest method in terms of implementation, the best method in terms of efficacy, but presents poor performance in terms of chromaticity shift, and it presents nonlinear luminous flux versus current [20]. BLM presents good performance with regards to efficacy, which is more complex to implement and performs less satisfactory compared to conventional PWM technique in terms of color stability [20, 21]. PWM is characterized by an intermediary performance, presenting poor efficacy compared with AM and BLM, but is simple to implement; it has linear response between luminous flux and duty cycle and presents stability of chromaticity shift [20, 22]; due to this balanced performance, PWM was chosen to drive LED in the proposed circuit.

The electronic circuit used to drive the LEDs is composed of an integrated power converter (IPC) formed by a buck–boost converter, which is able to perform the power factor correction (PFC), integrated with a forward converter, which made the power control (PC) of LEDs. This electronic topology was proposed in [23, 24] and was chosen because it can perform PFC and PC in only one IPC that shares the main switch. Additionally, the forward converter provides current source output, which is ideal for supplying LEDs. Figure 7 shows the IPC prototype.

The IPC provides its output as a current signal with constant value, e.g., 150mA; in this case, this constant forward current is transformed in PWM using two MOSFET switches, each of them responsible for adjusting the duty cycle and, consequently, the average forward current of each color of LED. The duty cycle reference is provided by the algorithm for CCT and luminous flux calculation, given by equation (1) and programmed in the MCU. A duty cycle with switching frequency of 1kHz was used in PWM; this value was limited by the sample rate and memory of used MCU. This frequency is slightly smaller than the recommendation of IEEE Standard 1789–2015 [25], which is 1.25kHz; however, it was not observed in light modulation or flicker in the chosen frequency. The LEDs are arranged in series and assembled in a heat sink as shown in Fig. 8. The series connection of each branch of array is to allow current measurement separately, enabling the individual current control and resulting in the same light intensity of all LEDs of branch.

Control system

A closed-loop system was created where the reference values of luminous flux and CCT were chosen by the user via mobile application in manual mode or by the algorithm, in automatic mode, following the pattern shown in Fig. 3 synchronized with time.

Based on the design parameters shown in Fig. 6, the MCU algorithm generates a reference current value and controls the semiconductor switches that regulate the LEDs average current through PWM duty cycle.

Fig. 7 Integrated power converter prototype

Fig. 8 LED arrays used in testing
Current sensors composed of a shunt resistor circuit are used to convert the current signal to voltage, which are then read by the MCU. Temperature sensor provides the heat sink temperature \( T_{hs} \) feedback that is compensated by the control loop. A proportional–integral (PI) controller was developed using a software application that guarantees zero error rate in a steady state. The system transfer function \( GP \) is basically a relation between the peak current \( I_{pk} \) and the duty cycle \( D \), that produces an average current, represented in (5):

\[
GP = I_{pk} \cdot D
\] (5)

Figure 10 shows the control closed-loop system diagram. The PI controller was designed considering the transfer function and dynamic of the sensor (H) implemented, which has a low-pass bandwidth to filter the current noise. The transfer function of PI controller implemented is represented in (6):

\[
G_pH(s) = \left( \frac{0.03937s^2 - 141.7s + 1.276.10^5}{s^2 + 2272s + 8.505.10^5} \right)
\] (6)

The system response was designed to have a null error in steady state, accommodation time of 118 ms, rise time of 64.4 ms, and no overshoot, being stable to this application. The controller equation implemented in the microcontroller is represented in (7):

\[
G_c(z) = \left( \frac{0.1113z + 0.1113}{z^2 - z} \right)
\] (7)

The control system shown in Fig. 10 was implemented in the assembly shown in Fig. 9. This hardware in conjunction with the IPC was used to adjust CCT and luminous flux of LEDs.

**Experimental results**

Based on the proposed system, as shown in Fig. 2, using an IPC shown in Fig. 7 in conjunction with the control board of Fig. 9, experimental tests were conducted utilizing the LEDs shown in Fig. 8 and a smartphone running the developed application with screens of Fig. 4. To capture the results, a setup was built using an oscilloscope to measure voltage and current, a spectrophotocolorimeter to measure the CCT and luminous flux, and a thermocouple to measure heat sink temperature. The setup is represented in Fig. 11.

The results of one test are represented in Fig. 12. This experiment was done within the two LEDs, varying the values of luminous flux and CCT in the app, calculating the current reference by these parameters in the microcontroller, and measuring these parameters with the setup shown in Fig. 11. Figure 13 presents the quantities measured by current probes in LEDs array. The red and blue lines are represented by 50mA/div and 0.5ms/div on the screen, where the red line is current in cool white LED and the blue line is current in warm white LED.

Table 2 shows a comparison between reference and measured results. It is observed that the maximum difference between reference and measured results was 3.35% for CCT and 5.57% for luminous flux.
Conclusion

In this paper, a system able to adjust the light intensity and CCT of a LED set composed of two arrays with different tons of CCT was proposed. Its main objective is providing comfortable lighting according to the circadian rhythm and offering benefits in the relationship between ambient lighting and human activities besides offering manual adjustment via remote control through a smartphone.

The proposed system is formed by a smartphone application connected by Wi-Fi which provides time synchronization to implement a CCT and intensity schedule following the pattern proposed in [16]. These reference values are inputted in a color-photo-electro-thermal algorithm, which, based on LED datasheet information, is able to calculate the forward current that synthetizes the accurate CCT mix and luminous flux to the two LED arrays. Finally, using an IPC proposed in [23, 24], the LED forward current is modulated using PWM in order to provide LEDs the required average current.

Experimental results show that the proposed system was able to receive manual or automatic requirements, generate reference values, and follow the reference with reduced and acceptable differences, less than 6%. This slight difference is due to detailed model employed in the algorithm used to provide CCT mix and luminous flux that consider color-photo-electro-thermal aspects of LED operation together, creating compensation to each interaction that occurs among these aspects.

Such system is useful to lighting designers that aim to control LEDs with different CCTs and to adjust luminous flux in an individual or jointly mode. Additionally, using patterns like the ones proposed in [16–18], it is possible to create systems that does not affect undesirably the circadian rhythm and, consequently, offer health and well-being for users.

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