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Ayarlanabilir Renk Sıcaklığına Sahip LED Armatürlerde Yenilikçi Yaklaşım

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Öz

Aydınlatma teknolojisi hızla gelişmektedir. Bu teknolojiler arasında, yüksek verimli ışık kaynakları olarak öne çıkan Işık Yayan Diyot (LED) sistemleri bulunmaktadır. LED'ler, çeşitli özellikler ve yapılarla üretilmektedir. Örneğin, RGB (Kırmızı Yeşil Mavi) LED'ler geniş bir renk yelpazesi üretebilmektedir. RGB LED'leri kullanarak, farklı renk sıcaklıklarına sahip beyaz ışık elde etmek de mümkündür. Renk sıcaklığı, gözlerimizin nesnelerin renklerini nasıl algıladığı üzerinde önemli bir rol oynar. Bir nesnenin gerçek renklerini, 6500K renk sıcaklığına sahip gün ışığı aydınlatması altında gözlemleyebiliriz. Aynı nesne, çeşitli renk sıcaklıklarına sahip aydınlatma altında farklı görünebilir. Sonuç olarak, tek bir aydınlatma armatüründe farklı renk sıcaklıklarını ayarlama ihtiyacı doğmuştur. Mevcut LED aydınlatma sistemleri, renk sıcaklığı ve parlaklığın hassas şekilde kontrol edilmesinde genellikle donanım entegrasyonu ve hesaplama verimliliği konularında sınırlamalar yaşamaktadır. Ayrıca, bu sistemler genellikle yüksek maliyetli sensörler gerektirmekte veya değişen çevresel koşullara uyum sağlayabilme esnekliğinden yoksun kalmaktadır. Bu eksiklikleri gidermek için önerilen sistem, PSoC teknolojisini AS7261 XYZ Kromatik Beyaz Renk Sensörü ile birleştirerek renk sıcaklığı ve parlaklık seviyelerini gerçek zamanlı olarak daha hassas ve maliyet etkin bir şekilde ayarlama imkanı sunmaktadır. Bu çalışmada, hem parlaklık hem de renk sıcaklığı açısından ayarlanabilir bir LED armatürü tasarımı, gömülü sistemler alanında giderek daha fazla önem kazanan PSoC (Programmable System on Chip) teknolojisi kullanılarak geliştirilmiştir. RGB LED'lerden oluşan armatürün renk sıcaklığına yönelik gerekli XYZ verileri, AS7261 XYZ Kromatik Beyaz Renk Sensörü'nden elde edilmiştir. Bu sensörden toplanan XYZ bilgileri, tasarlanan sistemin algoritmasında kullanılmıştır. RGB LED'lerin istenen renk sıcaklığı ve aydınlatma seviyesine göre çalıştığı parlaklık seviyeleri ayarlanarak sistem başarıyla uygulanmıştır. Bu yenilikçi yaklaşım, enerji verimli aydınlatma sistemleri, endüstriyel üretim süreçleri ve konut, ticari ve otomotiv ortamları için özelleştirilebilir aydınlatma çözümleri gibi pratik uygulamalara sahiptir ve yaygın endüstriyel benimseme potansiyelini vurgulamaktadır.

Anahtar kelimeler: CCT ayarlanabilir LED armatür, CCT kontrol, Gömülü PSoC sistemi

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Innovative Approach to Adjustable Color Temperature in LED Luminaires

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Abstract
The field of lighting technology is rapidly evolving. Among these technologies, Light Emitting Diode (LED) systems stand out as highly efficient light sources. LEDs are manufactured with various characteristics and structures. For instance, RGB (Red Green Blue) LEDs are capable of producing a wide spectrum of colors. By using RGB LEDs, it is also possible to achieve white light with different color temperatures Color temperature plays a crucial role in how our eyes perceive the colors of objects. We can observe the true colors of an object under daylight illumination with a color temperature of 6500K. The same object may appear differently under lighting with various color temperatures. Consequently, there has arisen a need to adjust different color temperatures within a single lighting fixture. Existing LED lighting systems often struggle with achieving precise control over color temperature and brightness due to limitations in hardware integration and computational efficiency. Additionally, these systems may require costly sensors or lack the flexibility to adapt to varying environmental conditions. To address these gaps, the proposed system integrates PSoC technology with an AS7261 XYZ Chromatic White Color Sensor, enabling real-time adjustments of color temperature and brightness with enhanced precision and cost-effectiveness. In this study, a design of an adjustable LED luminaire in terms of both brightness and color temperature has been developed using PSoC (Programmable System on Chip) technology, which is gaining significant traction and importance in the field of embedded systems. The necessary XYZ data for the color temperature of the luminaire, which consists of RGB LEDs, were obtained from the AS7261 XYZ Chromatic White Color Sensor. The XYZ information gathered from this sensor was utilized in the algorithm of the designed system. By adjusting the brightness levels at which the RGB LEDs operate according to the desired color temperature and illumination level, the system was successfully implemented. This innovative approach has practical applications in energy-efficient lighting systems, industrial production processes, and customizable illumination solutions for residential, commercial, and automotive environments, highlighting its potential for widespread industrial adoption.

Keywords: CCT tunable LED luminaire, CCT control, Embedded PSoC system

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1. Introduction

Electromagnetic waves consist of electric and magnetic fields moving perpendicular to each other in a coordinated manner. The portion of electromagnetic waves that can be perceived by the human eye is called "visible light." The smallest wavelength of visible light is 380 nm (violet) and the largest wavelength is 780 nm (red). Our eyes can only see wavelengths between 380–720 nm and cannot perceive all electromagnetic waves. Objects appear colored based on the absorption and reflection of light rays with wavelengths in the visible range. Color can be physically defined as a measure of which wavelengths a specific light ray contains and in what proportions, and light is necessary for the observation of color [1]. The temperature of a light source that has the same color coordinates as the radiation color of a black body at a specific temperature is called 'Color Temperature.' This relates not to the heat output of the light source but to the color of the light output. The CIE (Commission internationale de l'éclairage) also recommends expressing the closeness of temperatures to ideal distributions in Kelvin (K). At this point, the CCT (Correlated Color Temperature) magnitude is defined as a measure of how closely the emission of visual artificial light sources resembles the theoretical black body radiation at a specific temperature [2]. In this study, the PSoC embedded system was used to adjust the brightness of the designed luminaire, obtain the XYZ information from the AS7261 XYZ Chromatic White Color Sensor according to the changing brightness, and ensure the operation of the luminaire according to the developed algorithm. PSoC technology, which is rapidly gaining popularity today, holds an important place in embedded systems due to its significant features such as allowing the simultaneous use of analog and digital blocks and its ease of use. The PSoC family consists of devices that feature a controlled mixed-signal array on a single chip. These devices are designed to integrate many traditional microprocessor-based system components into a programmable, low-cost single chip. The PSoC device includes configurable analog and digital circuit elements as well as programmable interconnects. This structure offers configurations that the user can adjust as desired, thus meeting the requirements of many applications. In addition to these features, it includes a fast CPU, flash program memory, SRAM data memory, and configurable inputs and outputs [3].

Figure 1 shows the PSoC CY8CKIT-059 kit used in the study. This kit uses the CY8C5888LTI-LP097 68-pin PSoC 5LP chip, which has an M3 cortex. The CY8C5888LTI-LP097 chip features an 80MHz CPU (Central Processing Unit) speed, 256kb flash, 64kb sram, 2kb eeprom, 1x20-bit delta sigma adc, 2x12-bit sar adc, 4 dacs, 4 comparators, 4 sc/ct analog blocks, 4 opamps, 24 udbs, 4 16-bit timer/pwm, and a total of 48 input/output pins.

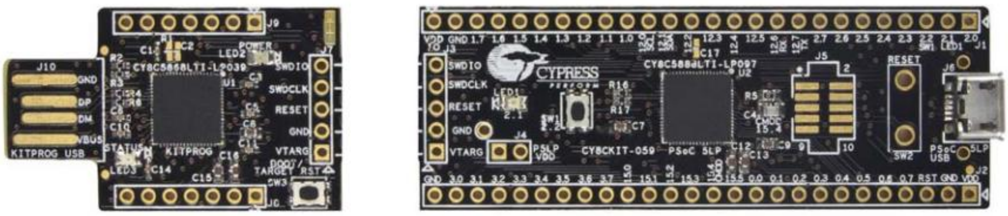

Figure 1. PSoC CY8CKIT-059 Kit [4]

Fedasyuk et al. [5] attempted to solve the problem of developing magnetic tracking sensors for high-precision object localization within the concepts of the Internet of Things and virtual reality using PSoC 5LP. Alakananda and Venugopal [6] tested the operation and performance of a quadcopter. In their study, the PSOC 6 was used, featuring a dual-core processor, which allows for simultaneous data sampling and processing. PSOC 6 was chosen due to its power efficiency, which enhances battery life or flight time. Kim et al. [7] proposed an LED matrix headlight system that reduces communication burden by using bilinear interpolation shift and masking operations, allowing fine adjustments in brightness and color with minimal data transfer. Liu et al. [8] demonstrated an energy-efficient embedded system for electrical engineering automation, integrating fuzzy logic with a PID control algorithm to optimize energy consumption. Their findings, implemented in a tunnel lighting project, revealed a significant energy savings rate of up to 51% per day, showcasing the potential of embedded systems in enhancing energy efficiency. Satvaya et al. [9], developed an outdoor luminaire based on LEDs that can wirelessly control illuminance, CCT, color rendering index (CRI), and spectral power using a microcontroller and pulse width modulation (PWM) technique. The system, controlled via a smartphone, demonstrated a wide range of color temperature options, enhanced spectral power, improved CRI, and the ability to create a calming nocturnal lighting ambiance. Barbadekar and Patil [10] proposed a PSoC-based smart antenna system, which offers features such as reliability, reconfigurability, automatic steering, and low cost. Ghoroury et al.[11] designed a color temperature adjustable white LED based on a newly developed monolithic color-tunable LED structure, capable of producing white light in the range of 2700 K to 6500 K. Kumar et al.[12] proposed a stand-alone, cost-effective, and innovative design for comprehensive online analysis of arc welding processes using PSoC embedded systems. Rafał Kociszewski [13] demonstrated the practical application of a PI controller using the PSoC embedded system. Tasci and Erol [14] designed a multi-channel wireless communication system using a PSoC and an RF transceiver module. Wojtkowski and Kociszewski [15] utilized SPDM (Stochastic Pulse Density Modulation) in their PSoC-based LED application to minimize harmonic effects. Lin et al. [16] developed a photometric optimization model for color temperature (CCT) tunable white LED clusters under the constraint of color rendering index (CRI), including downconversion energy loss. Lovasoa et al. [17] experimentally analyzed white LEDs with a wavelength of 445 nm. Using different module configurations, they examined the variations in different photometric parameters according to varying supply voltages. Nandhini et al. [18] implemented a color detection application for a wireless robotic arm using PSoC, utilizing LabVIEW graphical language for virtual instrument programming. Komiyama et al.[19] developed a prototype to demonstrate wireless visible light communication using RGB LEDs, with PSoC used to control the parallel signal communication provided by the RGB LEDs. He and Zeng [20] designed a simulation program capable of predicting not only the spectral power distribution, chromaticity coordinates, CCT, and color rendering index (CRI) but also the drive currents, luminous flux, input power, and luminous efficacy of white light LEDs. Chang et al. [21] developed a mixed light control module with RGB LEDs by integrating a photodiode with PSoC. In this study, the sensor was used to examine the ambient temperature and feedback voltage levels of the RGB photodiodes. Yang et al. [22] presented a reflection-based color measurement using a tricolor LED. The color of the tested sample was determined by measuring the three reflective intensities of different colors. A modulation/demodulation technique was used to distinguish the three reflected intensities. The three reflected signals could be processed by a computer to provide an (x, y) coordinate on the CIE chromaticity diagram. Since the three-terminal measurements provide insufficient predictions for an entire spectral reflection, a calibration procedure was successfully developed to correct the predicted results, which significantly differed from the values measured by a well-calibrated device. Speier and Salsbury [23] reviewed efficient white light LED systems with adjustable color temperatures (CT) ranging from 3000 K to 6500 K. Cho et al.[24] examine the historical development, technological advancements, and future potential of white light-emitting diodes (LEDs). The study focuses on the evolution of blue LED chips, device architecture, and the role of phosphors in generating white light. It highlights the commercial success of the blue LED and phosphor combination due to its energy efficiency and durability. While noting the limitations in color rendering capabilities, the authors report remarkable performance metrics, such as a luminous efficacy reaching up to 303 lm/W. The study also discusses the future potential of smart LED applications.

2. Color Space

Due to the vast diversity of colors, there arose a need to group and standardize these colors, leading to the concept of color space. Color spaces are mathematical models used to define colors. They are designed to represent all colors and are typically constructed in three dimensions. This is because, according to Grassmann's first law, which forms the basis of colorimetry, three independent variables are needed to determine a color. The positions of colors within the color space are determined by these variables. Each color space has its own standards for color generation. While constructing color spaces, it should be possible to transform from one color space to another using linear or non-linear methods[25].

Different devices for color display and processing use different color spaces. For instance, televisions, computer monitors, and scanners use the RGB color space, while printers and plotters use the CMY(K) color space. Color spaces are generally divided into two groups: device-dependent and device-independent color spaces. In device-dependent color spaces, colors are produced based on the characteristics of the device, meaning they are entirely dependent on the device's technical specifications. Device-independent color spaces, on the other hand, are developed by the CIE (Commission Internationale de L'Eclairage) and are used for color measurement in colorimetry, ensuring consistent color measurement across all colors. In these color spaces developed by the CIE, definitions and standards related to color (such as the standard observer and standard illuminant) are utilized [26]. Figure 2 presents the Planckian locus and the CIE 1931 chromaticity diagram, which determine the colors and color temperature of light sources.

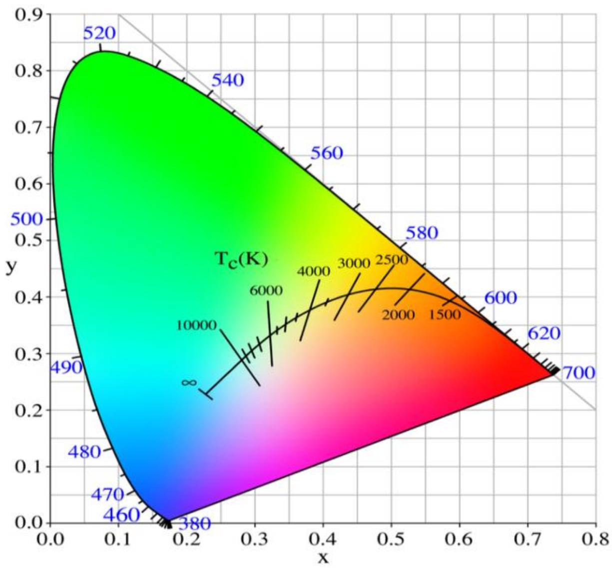

Figure 2. Planckian locus 1931 chromatic diagram in CIE 1931

The X, Y, and Z values are the sum of the signals sent to the brain by the nerves that perceive the three primary colors (red, green, blue). Each of these three signals, in relation to the total amount of stimulus, defines the color. While the brain combines these three magnitudes, it uses ratios to achieve the overall perception of color. The sum of the X, Y, and Z values equals the total visual perception of the color[27]. The proportion of red perception within this total is given by Equation 1, the proportion of green perception by Equation 2, and the proportion of blue perception by Equation 3. The calculated x, y, and z values are in the range of 0-1 and their total must be 1.

$$x = \frac{\sum_{i=1}^{S} X_i}{\sum_{i=1}^{S} X_i + Y_i + Z_i} \quad (1)$$

$$y = \frac{\sum_{i=1}^{S} Y_i}{\sum_{i=1}^{S} X_i + Y_i + Z_i} \quad (2)$$

$$z = \frac{\sum_{i=1}^{S} Z_i}{\sum_{i=1}^{S} X_i + Y_i + Z_i} \quad (3)$$

Using Equations 1 and 2, the coordinates of the color on the chromaticity diagram can be determined. According to the tristimulus theory of color perception, color can be represented by three parameters. In 1931, the CIE introduced the three primary colors, denoted as X, Y, and Z, which are calculated using Equations 4, 5, and 6. Here, r(λ) represents the spectral reflectance; P(λ) represents the spectral power distribution of the illuminant; and x(λ), y, and x(λ) , y(λ) , z(λ) are the CIE color matching functions. The CIE color matching functions are shown in Figure 3.

$$x=\int r(\lambda)P(\lambda)\bar{x}(\lambda)d\lambda \tag{4}$$
$$y=\int r(\lambda)P(\lambda)\bar{y}(\lambda)d\lambda \tag{5}$$
$$z=\int r(\lambda)P(\lambda)\bar{z}(\lambda)d\lambda \tag{6}$$

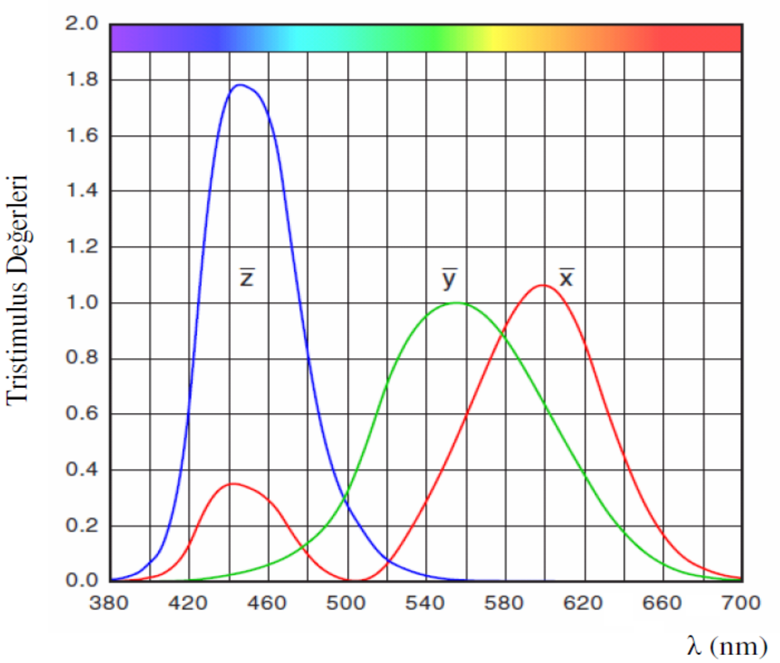

Figure 3. XYZ color matching functions [24]

3. Measurement Procedures With As7261 Spectral Sensor

In this study, the XYZ values were measured to ensure that the designed LED RGB luminaire operates at the desired color temperature and illumination level. The measurement of XYZ values was carried out using the AS7261 XYZ Chromatic White Color Sensor, as shown in Figure 4.

Figure 4. AS7261 XYZ Chromatic White Color Sensor

The AS7261 is a chromatic white color sensor that provides direct XYZ color coordinates consistent with the CIE 1931 2° Standard Observer color coordinates. The AS7261 controls the light entering the sensor array by integrating Gaussian filters through nano optic deposited interference filter technology into standard CMOS silicon. Control and spectral data access are provided via I²C or a serial UART [28]. The field of view of the AS7261 sensor's LGA package is shown in Figure 5.

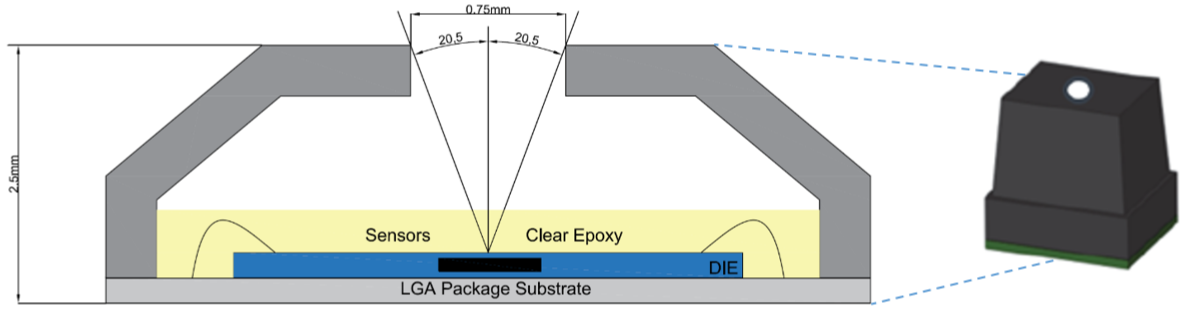

Figure 5. AS7261 LGA Package Field of View [24]

To examine how the brightness of the RGB LED luminaire changes according to the XYZ information, the experimental setup shown in Figure 6 was established. The brightness level of the RGB LED luminaire was adjusted in the range of 0-255 using the PWM blocks of the PSoC 5LP. The brightness level of the luminaire was controlled with the help of an LED driver connected to the output pins of the PSoC 5LP. Changes in brightness levels were measured using the AS7261 sensor, which was connected to another PSoC 5LP kit via I2C. The measured values were read as XYZ values from the computer connected to the PSoC via UART.

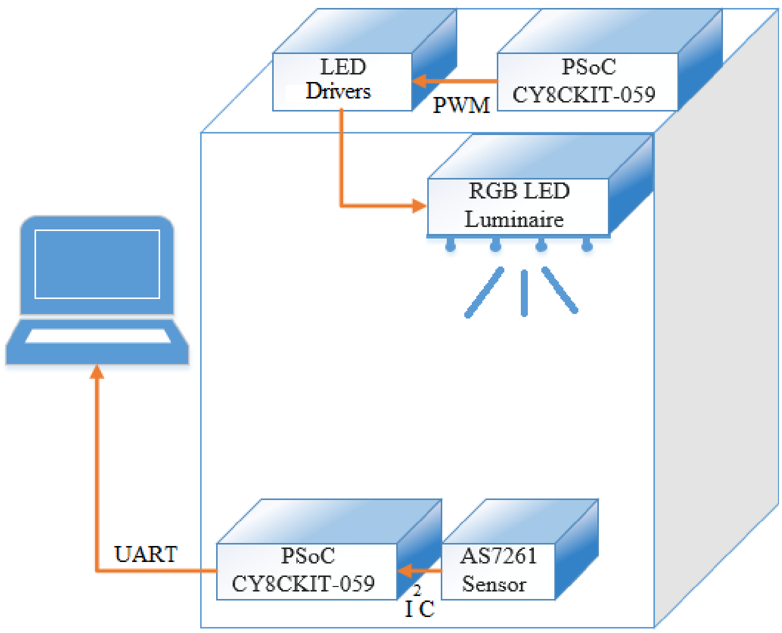

Figure 6. Experimental setup set up to read XYZ values

In the experimental setup, the PWM values for the red, green, and blue LEDs were individually varied within the range of 0-255. The XYZ values were recorded for each LED's PWM variation. These recorded values, obtained from experimental studies, are point values. There is no continuous function definition among the data. In such cases, the data are given as pairs of points $(x_1, y_1), \ldots, (x_n, y_n)$. It is desired to find a function $f(x)$ such that $f(x_j) \approx y_j$ for $j = 1, \ldots, n$. In other words, it is necessary to perform curve fitting to determine another function that is closest to the given point-by-point function values or to replace practically difficult-to-use functions with ones that can facilitate calculations.

For the obtained XYZ values, graphs were plotted using Matlab's curve fitting application. Curve fitting was applied to the plotted graphs. Initially, curve fitting was performed for the XYZ values of each color, resulting in a total of 9 fittings. However, upon further examination, it was observed that the differences in the fitted curve values were significant. Therefore, the curve fitting process was repeated by dividing the XYZ values of each color into three segments. As a result, 9 second-degree equations were obtained for each color, totaling 27 equations.

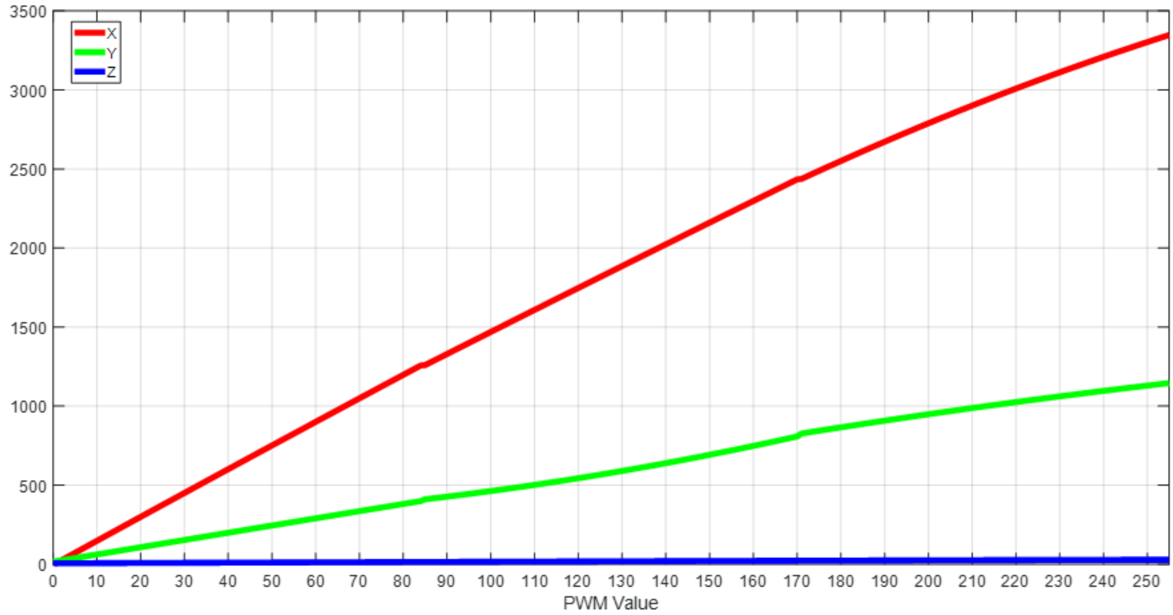

Figure 7. Red XYZ PWM exchange

The variation of the XYZ values for the red LED according to the PWM values varied in the range of 0-255 is shown in Figure 7. Nine fitted equations, numbered in the order in Figure 7, are given in equations 7-15.

$$-1.607*((R-42.5)/24.39)^2 + 366.2*((R-42.5)/24.39)+638.3 \tag{7}$$

$$-0.2844*((R-42.5)/24.39)^2 + 111.4*((R-42.5)/24.39)+210.1 \tag{8}$$

$$-0.009132*((R-42.5)/24.39)^2 + 2.476*((R-42.5)/24.39)+9.569 \tag{9}$$

$$-1.466*((R-127.5)/24.97)^2 + 345.1*((R-127.5)/24.97)+1851 \tag{10}$$

$$10.85*((R-127.5)/24.97)^2 + 116.7*((R-127.5)/24.97)+577.8 \tag{11}$$

$$-0.01346*((R-127.5)/24.97)^2 + 2.331*((R-127.5)/24.97)+17.83 \tag{12}$$

$$-14.33*((R-213)/24.68)^2 + 267.4*((R-213)/24.68)+2934 \tag{13}$$

$$-4.51*((R-213)/24.68)^2 + 93.77*((R-213)/24.68)+999 \tag{14}$$

$$-0.1109*((R-213)/24.68)^2 + 1.808*((R-213)/24.68)+25.09 \tag{15}$$

Equations 7, 8, and 9 represent the XYZ values for PWM ranges from 0 to 84. Specifically, Equation 7 calculates the X value, Equation 8 calculates the Y value, and Equation 9 calculates the Z value. For the PWM range of 85 to 170, Equations 10, 11, and 12 are used, where Equation 10 determines the X value, Equation 11 determines the Y value, and Equation 12 determines the Z value. Finally, for PWM values ranging from 171 to 255, Equations 13, 14, and 15 are employed. Equation 13 calculates the X value, Equation 14 calculates the Y value, and Equation 15 calculates the Z value. These equations are crucial for determining the appropriate PWM values to achieve the desired color temperature and brightness in the LED luminaire.

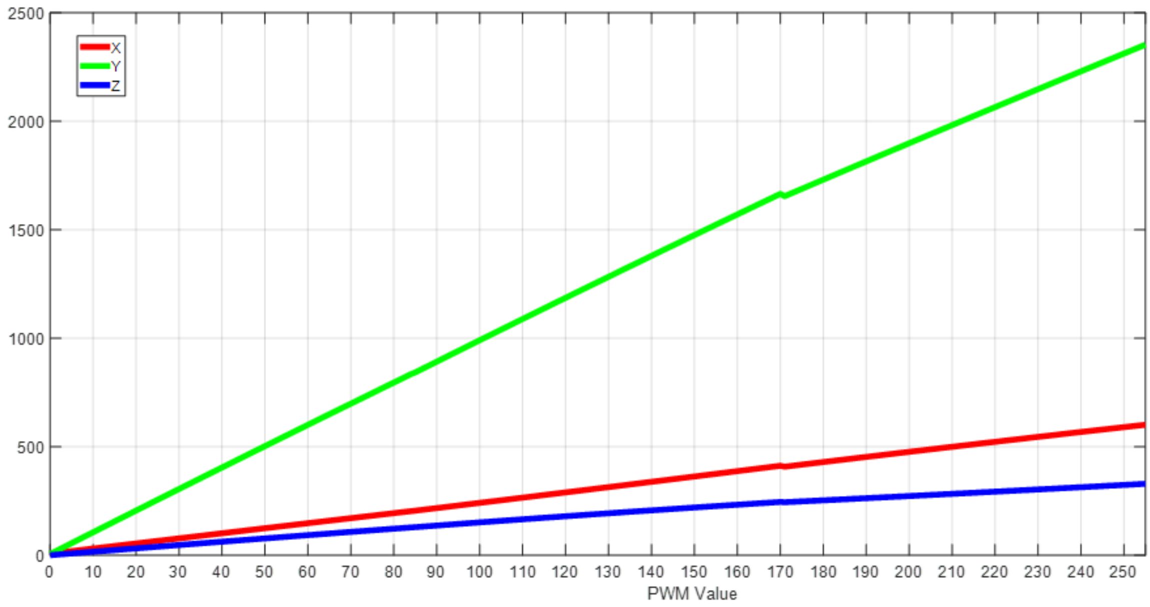

Figure 8. Green XYZ PWM variation

The variation of the XYZ values for the green LED according to the PWM values varied in the range of 0-255 is shown in Figure 8. Nine fitted equations, numbered in the order in Figure 8, are given in equations 16-24.

$$-0.21*((G-42.5)/24.39)^2+ 56.86*((G-42.5)/24.39)+107 \quad (16)$$

$$-1.339*((G-42.5)/24.39)^2+ 240.6*((G-42.5)/24.39)+428.9 \quad (17)$$

$$-0.3941*((G-42.5)/24.39)^2+ 37.07*((G-42.5)/24.39)+66.22 \quad (18)$$

$$0.3643*((G-127.5)/24.97)^2+ 60.81*((G-127.5)/24.97)+307.8 \quad (19)$$

$$-1.77*((G-127.5)/24.97)^2+ 241.7*((G-127.5)/24.97)+1259 \quad (20)$$

$$-0.869*((G-127.5)/24.97)^2+ 34.07*((G-127.5)/24.97)+190 \quad (21)$$

$$-0.6235*((G-213)/24.68)^2+ 56.83*((G-213)/24.68)+506.6 \quad (22)$$

$$-1.166*((G-213)/24.68)^2+ 205.1*((G-213)/24.68)+2007 \quad (23)$$

$$0.3105*((G-213)/24.68)^2+ 24.95*((G-213)/24.68)+285.9 \quad (24)$$

For the PWM range of 0 to 84, Equations 16, 17, and 18 are used, where Equation 16 calculates the X value, Equation 17 calculates the Y value, and Equation 18 calculates the Z value. In the PWM range of 85 to 170, Equations 19, 20, and 21 are employed, with Equation 19 determining the X value, Equation 20 determining the Y value, and Equation 21 determining the Z value. For the PWM range of 171 to 255, Equations 22, 23, and 24 are used, where Equation 22 calculates the X value, Equation 23 calculates the Y value, and Equation 24 calculates the Z value. These equations are essential for adjusting the PWM values to achieve the desired color temperature and brightness for the Green LED in the luminaire.

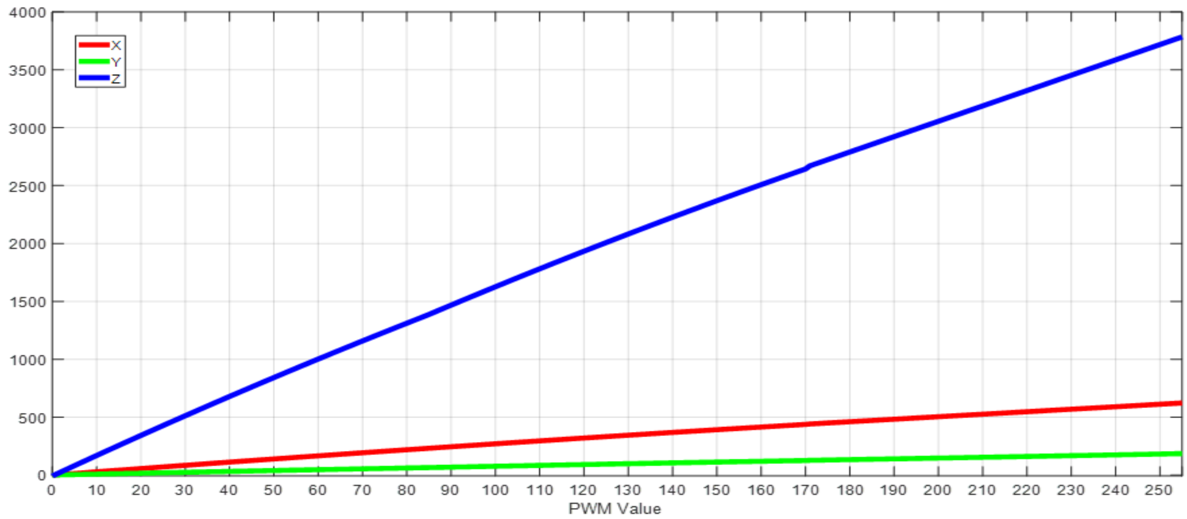

Figure 9. Blue XYZ PWM variation

The variation of the XYZ values for the blue LED according to the PWM values varied in the range of 0-255 is shown in Figure 9. Nine fitted equations, numbered in the order in Figure 9, are given in equations 25-33.

$$-1.081*((B-42.5)/24.39)^2+ 66.64*((B-42.5)/24.39)+118.8 \quad (25)$$

$$-0.2957*((B-42.5)/24.39)^2+18.51*((B-42.5)/24.39)+33.52 \quad (26)$$

$$-10*((B-42.5)/24.39)^2+400*((B-42.5)/24.39)+720 \quad (27)$$

$$-1.311*((B-127.5)/24.97)^2+60.5*((B-127.5)/24.97)+338.3 \quad (28)$$

$$-0.4176*((B-127.5)/24.97)^2+17.98*((B-127.5)/24.97)+96.44 \quad (29)$$

$$-10.21*((B-127.5)/24.97)^2+369.1*((B-127.5)/24.97)+2045 \quad (30)$$

$$-0.07585*((B-213)/24.68)^2+53.26*((B-213)/24.68)+532.1 \quad (31)$$

$$0.2312*((B-213)/24.68)^2+17.03*((B-213)/24.68)+155.8 \quad (32)$$

$$-0.1808*((B-213)/24.68)^2+327.2*((B-213)/24.68)+3228 \quad (33)$$

For the PWM range of 0 to 84, Equations 25, 26, and 27 are used, where Equation 25 calculates the X value, Equation 26 calculates the Y value, and Equation 27 calculates the Z value. In the PWM range of 85 to 170, Equations 28, 29, and 30 are employed, with Equation 28 determining the X value, Equation 29 determining the Y value, and Equation 30 determining the Z value. For the PWM range of 171 to 255, Equations 31, 32, and 33 are used, where Equation 31 calculates the X value, Equation 32 calculates the Y value, and Equation 33 calculates the Z value. These equations are essential for adjusting the PWM values to achieve the desired color temperature and brightness for the Blue LED in the luminaire.

4. Obtaining PWM Ratios

Color temperature can be determined using the x and y coordinate information obtained from Equations 1 and 2. In this study, the x and y coordinate information for color temperature values of 3000K, 4000K, and 5000K were taken from Figure 10. For example, for 5000K, x = 0.346 and y = 0.362. The calculation of the CCT value from these x and y coordinates is performed using Equations 34 and 35.

$$n=(x-0.3320)/0.1858-y) \quad (34)$$

$$CCT=449n^3+3525n^2+6823.2n+5520.33 \quad (35)$$

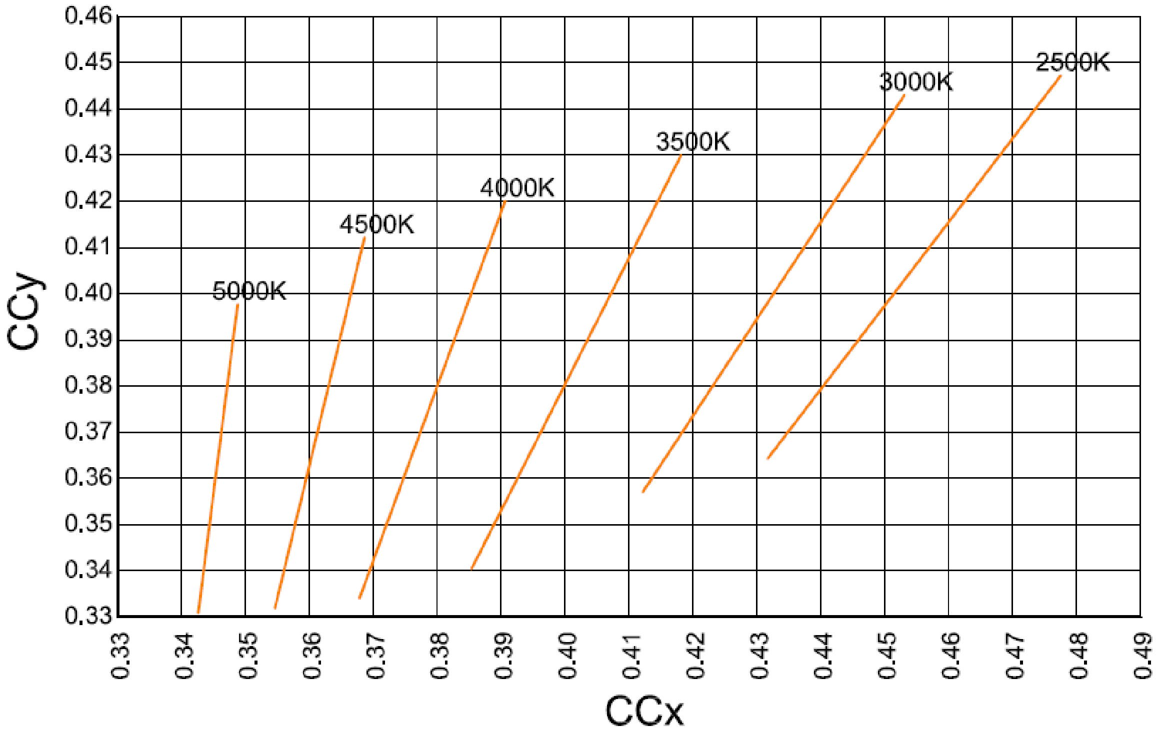

Figure 10. CCT change according to xy coordinates

For the brightness level, the Y data from the AS7261 XYZ Chromatic White Color Sensor is used. Accordingly, the target X and Z values are calculated using Equations 36 and 37.

$$X=x*(Y/y) \quad (36)$$
$$Z=(Y/y)*(1-x-y) \quad (37)$$

After calculating the X, Y, Z, x, and y values for the target color temperature and brightness level, the PWM values need to be determined. Using the equations obtained from curve fitting in the previous section, we determine the appropriate PWM values.

For an RGB LED, a separate PWM value needs to be determined for each color. The intersection point of the xy coordinates of the determined PWM values for the RGB LEDs provides the desired color temperature and brightness level.

For example, let's select 5000K and a brightness level of Y = 3000. From Figure 10, x = 0.346 and y = 0.362 are found. Substituting these values into Equations 9 and 10, we find X = 2867.4 and Z = 2419.8. To achieve the desired XYZ values, the appropriate PWM curves need to be determined.

$$X_R= -1.466*((R-127.5)/24.97)^2 + 345.1*((R-127.5)/24.97)+1851 \quad (38)$$
$$Y_R= 10.85*((R-127.5)/24.97)^2 + 116.7*((R-127.5)/24.97)+577.8 \quad (39)$$
$$Z_R= -0.01346*((R-127.5)/24.97)^2 + 2.331*((R-127.5)/24.97)+17.83 \quad (40)$$
$$X_G=-0.6235*((G-213)/24.68)^2+ 56.83*((G-213)/24.68)+506.6 \quad (41)$$
$$Y_G=-1.166*((G-213)/24.68)^2+ 205.1*((G-213)/24.68)+2007 \quad (42)$$
$$Z_G=0.3105*((G-213)/24.68)^2+ 24.95*((G-213)/24.68)+285.9 \quad (43)$$
$$X_B=-0.07585*((B-213)/24.68)2+53.26*((B-213)/24.68)+532.1 \quad (44)$$
$$Y_B=0.2312*((B-213)/24.68)2+17.03*((B-213)/24.68)+155.8 \quad (45)$$
$$Z_B=-0.1808*((B-213)/24.68)2+327.2*((B-213)/24.68)+3228 \quad (46)$$

Using the equations, the PWM values are determined according to the targeted values. The obtained PWM values are substituted into Equations 47,48 and 49 to verify their accuracy.

$$X_T = X_R + X_G + X_B \quad (47)$$
$$Y_T = Y_R + Y_G + Y_B \quad (48)$$
$$Z_T = Z_R + Z_G + Z_B \quad (49)$$

For the PWM values, R = 133, G = 248, and B = 128 are found. When these values are substituted into Equations 11, 12, and 13, X = 2852.4, Y = 2996.35, and Z = 2392.64 are calculated. Substituting these values into Equations 7 and 8 yields a CCT value of 5000.2 K. Figure 11 shows the xy coordinates of the RGB LEDs for 5000K.

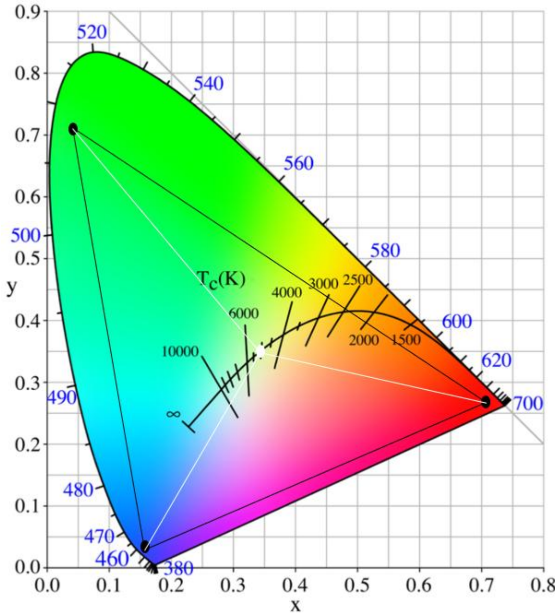

Figure 11. Representation of RGB LEDs in xy coordinates for 5000K

LEDs are preferred due to their low voltage operation, high efficiency, and long lifespan. To adjust the light intensity of an LED, an LED driver is required. LED drivers convert the AC or DC voltage at their input into a current and/or voltage suitable for the LED's operation. The selection of the driver is just as important as the selection of the LED in LED luminaires. If the correct LED driver is not chosen, the lifespan of the LEDs will be shortened. There are two main types of drivers on the market based on the driving methods for LEDs: constant voltage and constant current drivers. Constant voltage LED drivers are generally used with decorative lighting strips or bar LEDs, while constant current LED drivers are preferred in general lighting applications such as street lights and projectors. Constant current LED drivers drive the LEDs at desired currents such as 350, 500, 700, 1000, and 1400mA, with variable output voltages determined by the voltage drop across the LED [29].

Various ready-made driver circuits are available on the market for driving LEDs at constant current. In this PSoC-based study, the constant current C series product from ACG Electronics, shown in Figure 11, was used as the LED driver.

Figure 12. C series constant current LED driver circuit

Adjusting the brightness of an LED with a PWM signal is based on the principle of changing the average current of the LED. The average value of the PWM signal is given in Equations 50-52.

$$I_{ort} = \frac{1}{T}\int_0^T I(t)\,dt \tag{50}$$

$$I_{ort} = \frac{1}{T}\left[\int_0^{T_{on}} I_{max}(t)\,dt + \int_{T_{on}}^{T} I_{min}(t)\,dt\right] \tag{51}$$

$$I_{ort} = d \, . I_{max} \tag{52}$$

Since the minimum value of the signal is 0V, the average value is equal to the product of the duty cycle and the maximum value of the signal.

5. Programming The Designed System

In the designed system, the color temperature and brightness level at which the RGB LED luminaire will operate are selected using a touch LCD screen. The touch LCD screen is connected to the PSoC 5LP via UART. The values selected from the touch screen are transmitted to the PSoC. Based on the experiments conducted, the PSoC sends the obtained PWM values to the LED driver, as shown in Figure

13. By operating the RGB LEDs with different PWM values, the desired illumination levels are achieved.

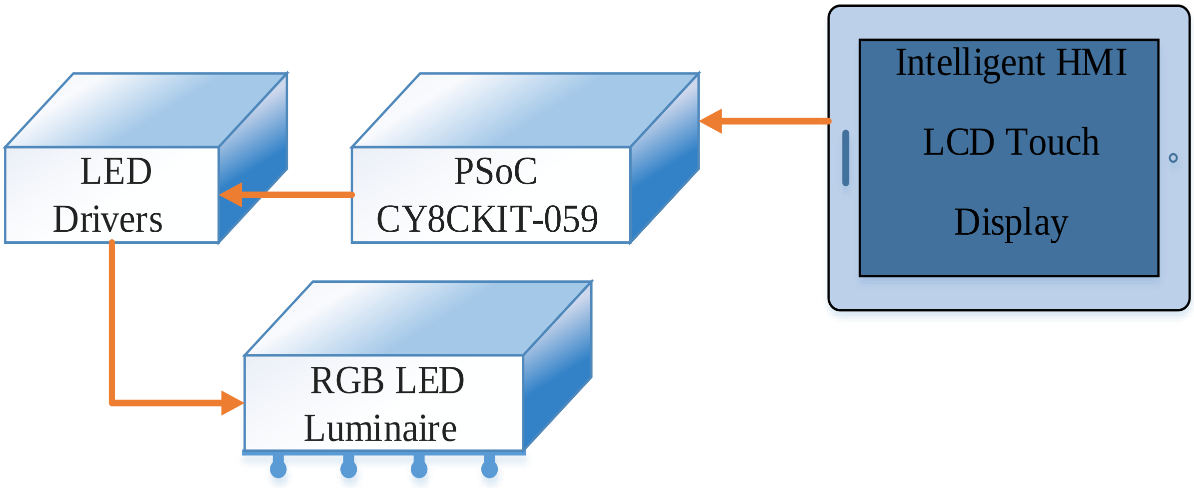

Figure 13. Block Diagram

In LED technology, manufacturers document a lifespan of up to 50,000-60,000 hours through testing. However, these tests are conducted under specific temperature conditions. Therefore, using a heat sink in luminaire design is very important. In this study, a heat sink was used to minimize the system's heating. The overall appearance of the designed system is shown in Figure 14.

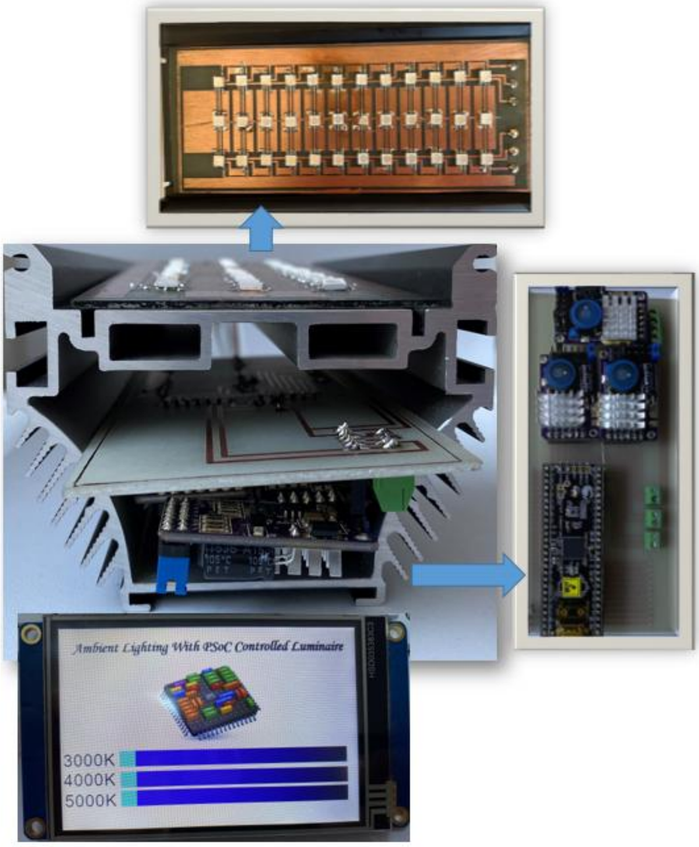

Figure 14. General view of the system

The designed RGB LED luminaire is made using 50x50 RGB LEDs. The circuit of the LED luminaire consists of 12 parallel groups. Each group contains 3 series-connected RGB LEDs.

6. Conclusion

In this innovative project, which integrates the AS7261 XYZ Chromatic White Color Sensor and the PSoC microcontroller, a design has been developed that can be particularly utilized by LED luminaire manufacturers. This study allows for the design of luminaires during the production phase based on precise data obtained from the AS7261 XYZ Chromatic White Color Sensor. The significant advantage of this system is that it eliminates the need to use a sensor in the design of every luminaire, thereby offering a cost-effective solution. This approach ensures accurate color and brightness control while reducing the overall production costs, making it a viable option for mass production of LED luminaires. The implementation of the PSoC microcontroller for managing the PWM signals provides precise control over the RGB LEDs, enabling the attainment of the desired color temperature and brightness levels. The flexibility and programmability of the PSoC platform allow for easy adjustments and scalability in production, accommodating various design requirements and preferences. Moreover, by utilizing a heat sink in the luminaire design, the system's longevity and performance are enhanced, ensuring that the LEDs operate within optimal temperature ranges. This contributes to the durability and reliability of the luminaires, meeting the high standards expected in modern lighting solutions. This project not only demonstrates the practical application of advanced sensor technology and embedded systems in lighting design but also provides a framework for future developments in the field. Future studies could explore the thermal effects of prolonged operation to optimize the system's performance and longevity. Additionally, addressing scalability challenges and investigating adaptability to diverse luminaire designs can expand the system's applicability. Future research could also explore ways to enhance the scalability of the system for industrial-scale applications and improve its adaptability to various luminaire designs. Additionally, integrating advanced control systems, such as IoT frameworks, could further expand the system's functionality and practical applications. The methodologies and findings presented can serve as a reference for further research and innovation, promoting the development of more efficient and versatile lighting systems. Overall, the integration of the AS7261 sensor with the PSoC microcontroller presents a robust and efficient approach to LED luminaire design, paving the way for enhanced performance, cost savings, and increased adaptability in the lighting industry.

7. Author Contribution Statement

All authors contributed equally to this study.

8. Ethics Committee Approval and Conflict of Interest

"There is no need for an ethics committee approval in the prepared article"
"There is no conflict of interest with any person/institution in the prepared article"

9. Ethical Statement Regarding the Use of Artificial Intelligence

During the preparation of this manuscript, the writing assistance tool 'Grammarly' was used solely for limited linguistic editing; all scientific content, analyses, and conclusions remain entirely the responsibility of the authors.

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