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Implementation of a Tunable RGB LED Light Source

[1]R. Srividya*, [2]Dr. Ciji.Pearl kurian, [3]C.R. Srinivasan, and [4]Dorde Velickovic

Abstract: There have been a lot of advancements in the luminaire technology which has resulted in the popularity of LED's (Light Emitting Diode). These light emitting diodes are being used almost everywhere mainly because of their high efficacy and possibility of controlling color. Any color can be produced by proper mixing of Red-Green-Blue LEDs. This paper, proposes the technique of generating different CCTs of white light located on the planckian locus of CIE 1931 by varying the driving current of a luminaire. This is done by Hardware in loop simulation using NI LabVIEW that takes the user preference and accordingly regulates the light output by providing the required control signals to the DAQ. This system uses DAQ to generate the PWM signals according to the mixing proportions thereby eliminating the need of microcontrollers. Switch mode power converters behave as a constant current source for the RGB LED luminaire. The implemented RGB LED light source that is dynamically tunable can be a good lighting fixture for mood lighting in hotels, entertainment halls, shops etc.

Keywords: Red-Green-Blue (RGB) LED, Hardware in loop simulation (HIL), Correlated ColorTempetature (CCT), Data Acquisition (DAQ)

1. INTRODUCTION

In traditional lighting design, color appearance of white light source typically remains fixed over the life of the system. The invention of LED lighting has led to the possibility of controlling the color. Apart from high efficacy, application of mood lighting has high market value. We can change the atmosphere of a room if we change the lighting. People tend to prefer neutral or cool sources at the office for their daytime activities and warmer sources at home for their evening activities. Thus different spaces have different color needs and these needs may change based on the time. Based on these market demands and optical efficiency of LEDs, multi-chip Red, Green and Blue (RGB) LED light sources attract more attentions[10] [2].The use of multichip multicolored LEDs allows the user to dynamically vary the color temperature, or set a particular color point without using the color filters. This is because LEDs are able to emit light in a wide variety of saturated colors[8]. Several methods are used to produce color tunable white light but external dynamic control can be achieved only by mixing multi-colored LEDs without phosphors. This makes it possible for the color temperature to either automatically change at various times of the day or in response to certain events or users can manually adjust the color temperature based on evolving space needs and occupant preference[7] [11]. That stabilizing the colors of Red-Green-Blue is a challenging task, which includes color light luminance control using switching mode power converters. Compared to Amplitude modulation Pulse Width Modulation (PWM) provides a stable forward current thereby reducing the non-linearity of the forward driving current to LED light and color. In this paper we propose a simple

1-2 Faculty of E & E Department, MIT, Manipal
3 Faculty of I&C Department, MIT, Manipal
4 Final year B.Tech, University of Cerbia
* e-mail: srividya.r@manipal.edu

practical technique for producing the correlated color temperatures from 2700K-6500K with an RGB LED luminaire using NI LabVIEW as the controller and DAQ for PWM generation.

2. EXPERIMENT: DEVICES AND PROCESS

A detailed view of the process of controlling the RGB LED lamp is shown in figure 1.For the desired CCT specified by the user, Tri-stimulus values (X Y Z) and the corresponding current levels and dimming factors (Dr Dg Db) were calculated by LabVIEW and were provided as control signals to the Data acquisition module. NI DAQ 6356 and TI LM3407 Data acquisition and driver board were selected for detailed study and illustration. Three PWM signals at a fixed frequency were generated by configuration of counter channels of NI X series USB 6356 DAQ. Red-Green and Blue LEDs were individually driven by LM 3407 which is a current controlled modified floating Buck Converter as shown in fig 2. The switching converter essentially behaves as a current source whose magnitude is controlled by a PWM signal. Component values have been optimized for fast transient of the output current under a PWM gate pulse which was applied at a switching frequency of 300 Hz to the DIM pin.

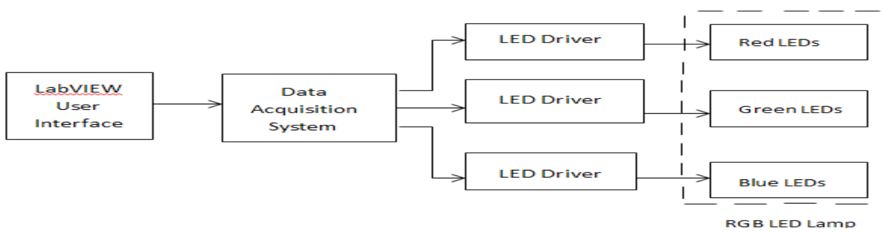


Figure 1: Block diagram of the process

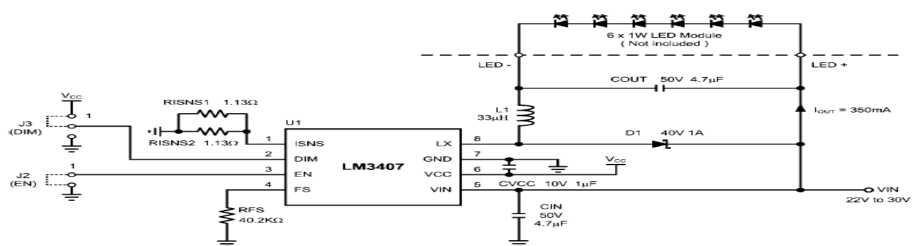


Figure 2: LM3407 Buck converter

2.1 SELECTION AND ARRANGEMENT OF LEDS ON HEAT SINK

LED's were selected based on their wavelength, luminous flux, forward current, luminous efficacy and reliability. Accordingly, Edixeon RGB 3W LEDs with the specifications given in table 1 were used.

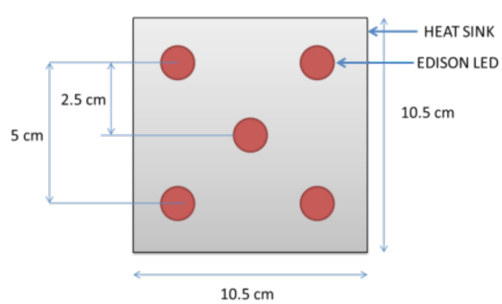


Figure 3: Arrangement of LED on heat sink

5 series connected LEDs were arranged on the heat sink in a star pattern as shown in fig 3. The thermal resistivity of the designed heat sink was 1.62 ^{o}C/W such that the heat sink provides enough cooling and there is no rise of junction temperature because of power dissipation.

Table 1
Specifications of RGB LED

Edixeon RGB LED	*Wavelength (nm)*	*Coordinate x*	*Coordinate y*	*Forward Voltage (V)*	*Forward Current (mA)*	*Luminous Flux (lm)*
RED	625	0.7006	0.2993	2.2	350	38
GREEN	528	0.1763	0.7228	3.4	350	65
BLUE	464	0.1512	0.0336	3.4	350	17

2.2 Review of RGB color mixing

In the spectrum, the visible light is in the wavelength range of 380nm to 780nm and the perceived color of light is referred to as the spectral color. Additive and subtractive color mixings are two approaches of color mixing. The primary colors used in additive color mixing are Red, Green and Blue. The most commonly used model is the CIE 1931 color space, a methodology for mapping the perceived color on to the unit plane of an x-y graph as shown in figure 4. Human vision is tri-chromatic in nature so the visible light from a light source appears as a combination of red, green and blue. Eye has any of these retinal sensitivity cones. These are called as Tri-stimulus sensitivities represented as X,Y,Z. These tri-stimulus values can be represented in 2D x-y coordinate as given in equation (1) ;

$$x = \frac{X}{X+Y+Z} \quad ; \quad y = \frac{Y}{X+Y+Z} \qquad (1)$$

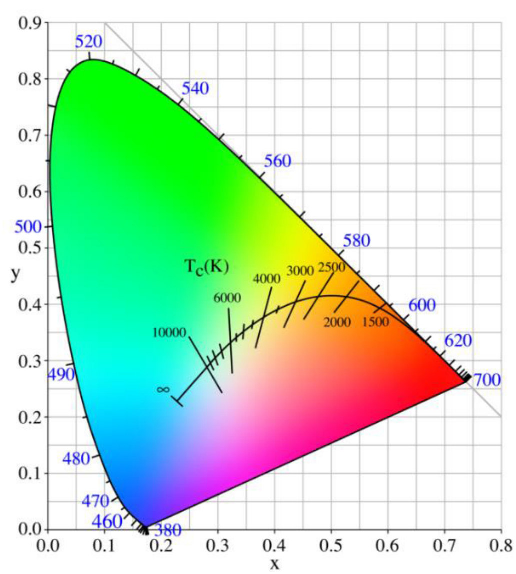


Figure 4: CIE 1931 Chromaticity Diagram

CCT is defined as the color temperature of white light with reference to a black body radiator produced from the mixing of these tri-stimulus values[7]. In order to exhibit the color stability of RGB light sources color deviation should be evaluated. However, because of the non-uniform distribution of Red, Green and blue areas on the CIE 1931 chromaticity diagram it is not easy to discriminate the difference of two colors with their distance. Therefore, the x-y plane is transformed to u-v plane and the resultant u-v plane is the

CIE 1960 u-v chromaticity diagram. The diagram gives an even color perceptible difference for the distance of two color points independent of the absolute positions of the color points. Co-ordinate transformation equation from x-y to u-v can be given as in equation (2);

$$u = \frac{4x}{-2x+12y+3} \quad ; \quad v = \frac{6y}{-2x+12y+3} \qquad (2)$$

Accordingly, the distance of two color points in u-v chromaticity diagram $\delta uv = \sqrt{(\delta u)^2 + (\delta v)^2} < 0.002$ is indistinguishable to humans. Errors within this small distance are considered to be acceptable in most applications. If we mix the light intensities of three LEDs with wavelengths 625, 528 and 464 nm we can produce all colors within the triangle whose corners are at the color coordinates of RGB LEDs[14]. The accuracy of the desired color light that was mixed by RGB LEDs is dependent on the stability of the color point of RGB LEDs and the accuracy of the dimming method.

2.3 Process of Color mixing

The law governing the color mixing algorithm is Grassman's Law, which states that the superposition of colors is a linear phenomenon, so that once a number of n primary emitters is defined, each having known color coordinates (x_k, y_k) on the color space, any color coordinates (X,Y) lying inside the polygon defined by the primary emitters can be synthesized, simply by linearly combining the primary emitter luminous fluxes.

$$X = \frac{\sum_1^n \frac{x_k Y_k}{y_k}}{\sum_1^n \frac{Y_k}{y_k}} \quad Y = \frac{\sum_1^n \frac{y_k Y_k}{y_k}}{\sum_1^n \frac{Y_k}{y_k}} \qquad (3)$$

The below matrix A given in (4) represents the linear combination of XY coordinates of three different primary emitters Red, Green and Blue with (x_m,y_m) representing the coordinates of the mixed colour.

$$A = \begin{bmatrix} \frac{x_R - x_m}{y_R} & \frac{x_G - x_m}{y_G} & \frac{x_B - x_m}{y_B} \\ \frac{y_R - y_m}{y_R} & \frac{y_G - y_m}{y_G} & \frac{y_B - y_m}{y_B} \\ 1 & 1 & 1 \end{bmatrix} \qquad (4)$$

Total lumen output from the lamp Y is sum of individual flux output. Y in matrix form can be represented as;

$$Y = \begin{bmatrix} Y_r \\ Y_g \\ Y_b \end{bmatrix} \quad Y = \begin{bmatrix} Y_r \\ Y_g \\ Y_b \end{bmatrix} \qquad (5)$$

Where, Yr, Yg and Yb are the respective lumen output of each LED also called as tri-stimulus values. The total lumen output matrix B can be given as;

$$B = \begin{bmatrix} 0 \\ 0 \\ Y_k \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 0 \\ Y_k \end{bmatrix} \qquad (6)$$

Calculation of the lumen output of each LED to get the desired color coordinates can be done by the below expression given as (7);

$$Y = A^{-1}.B \qquad (7)$$

Where A^{-1} can be solved by the expression given in (8) as;

$$A^{-1} = A^T(AA^T) \qquad (8)$$

Combining matrices of (4), (5) and (6) according to expression given in (7) we get;

$$\begin{bmatrix} Y_r \\ Y_g \\ Y_b \end{bmatrix} = \mathrm{INV}\begin{bmatrix} \frac{x_R - x_m}{y_R} & \frac{x_G - x_m}{y_G} & \frac{x_B - x_m}{y_B} \\ \frac{y_R - y_m}{y_R} & \frac{y_G - y_m}{y_G} & \frac{y_B - y_m}{y_B} \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} 0 \\ 0 \\ Y_k \end{bmatrix} \tag{9}$$

A simple program in MATLAB was developed to calculate the mixing proportions. Tristimulus proportions of Red, Green and Blue (Yr Yg Yb) or (X Y Z) were calculated for CCTs from 2700K-6500K by knowing the xy coordinates of the desired CCTs and xy coordinates of individual RGB LEDs. The total lumen output of lamp was fixed at 400 lumens. Results of calculations are tabulated in table 2[13]. xy coordinates of CCTs were taken according to CIE standard and were again verified using OSRAM color calculator.

Table 2

Results of color mixing algorithm

CCT (K)	*x Coordinate*	*y Coordinate*	*Tristimulus (lm)*			*Dimming Factor (%)*		
			X	*Y*	*Z*	*Dr*	*Dg*	*Db*
2700	0.4598	0.4105	159.34	236.8	3.84	77	61	3
3500	0.4053	0.3907	136.88	256	7.13	62	70	5
4000	0.3804	0.3766	127.64	263.2	9.12	56	73	7
4500	0.3608	0.3636	120.54	268.5	10.9	51	75	8
5000	0.3451	0.3516	115.02	272.3	12.7	48	77	10
5500	0.3324	0.341	110.59	279.2	14.2	45	80	11
6000	0.3221	0.3317	107.03	277.3	15.6	43	79	12
6500	0.3135	0.3236	104.01	279.1	16.9	42	80	13

3 SIMULATION AND EXPERIMENTAL RESULTS

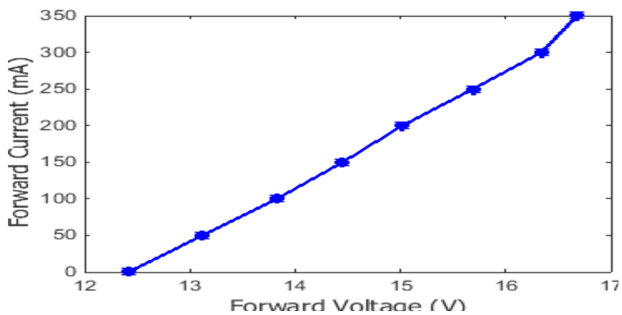
Initially, a small experiment was conducted to test the LEDs and plot their VI characteristics. The graphs are shown in figure 5 (a)-(c). Next, the theoretical calculations of the tri-stimulus values (X Y Z) and the dimming factors (Dr Dg Db) need to be experimentally verified. The experiment was conducted in controlled environment where LEDs were only source of light. The ambient temperature was maintained at 25^{o} C[10]. At most care was taken to avoid the rise of junction temperature by giving enough time between the readings such that Tj = Ta=25^{o}C. Theoretical values of (Dr Dg Db) were applied and then CCT was measured by spectro-radiometer. If the measured CCT value did not match with the theoretical value then dimming factors of each channel were finely tuned until perfect match was achieved. The corresponding tri-stimulus values and forward current applied were noted for each CCT. Results are in the region of tolerance as shown in table 3.

Table 3

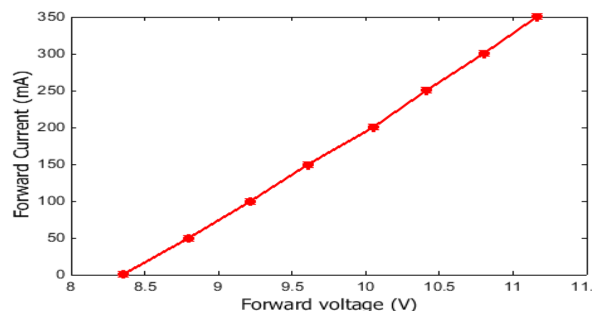
Experimental results of color mixing

CCT (K)	*x Coordinate*	*y Coordinate*	*Tristimulus (lm)*			*Dimming Factor (%)*			*Driving Current (mA)*		
			X	*Y*	*Z*	*Dr*	*Dg*	*Db*	*Ir*	*Ig*	*Ib*
2700	0.4598	0.4105	159	243	4	77	65	3	269.5	227.5	10.5
3500	0.4053	0.3907	139	259	7	63	71	5	220.5	248.5	17.5
4000	0.3804	0.3766	126	264	9	55	73	7	192.5	255.5	24.5
4500	0.3608	0.3636	118	273	12	50	77	9	175	269.5	31.5
5000	0.3451	0.3516	112	280	15	46	80	11	161	280	38.5
5500	0.3324	0.341	108	286	19	44	83	14	154	290.5	49
6000	0.3221	0.3317	103	289	21	41	84	16	143.5	294	56
6500	0.3135	0.3236	100	293	24	39	86	18	136.5	301	63

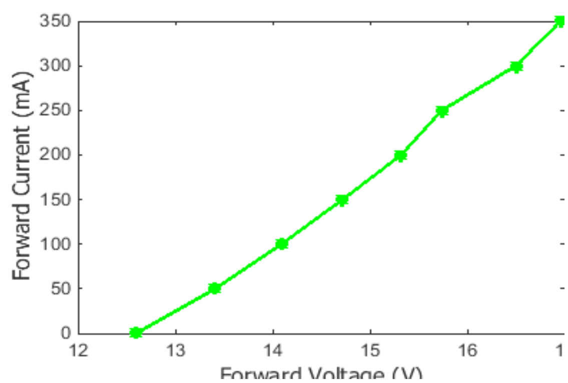
Stability or the accuracy of the color point depends on the accuracy of the driving technique[12]. There is a linear relationship between Tri-stimulus values (X Y Z) and Dimming factor (Dr Dg Db) [11]. This relationship can become highly non-linear if an inappropriate control method or working color range is used. It is because of this reason that PWM is preferred over AM. X-point, Y-point and Z point in the plots of fig 6 represent the X Y Z which are to be maintained for a CCT of 6500K at a forward voltage of 9.5, 16.5 and 13.3V and forward current of 136.5, 301 and 63 mA respectively. The Dr Dg Db values for 6500 K are 39%, 86% and 18% respectively for the selected RGB LED lamp. If the required duty cycles are normalized as 100% and when they are reduced to 80% the X, Y and Z points get shifted as shown in figure 6 (a)-(c).



(a)



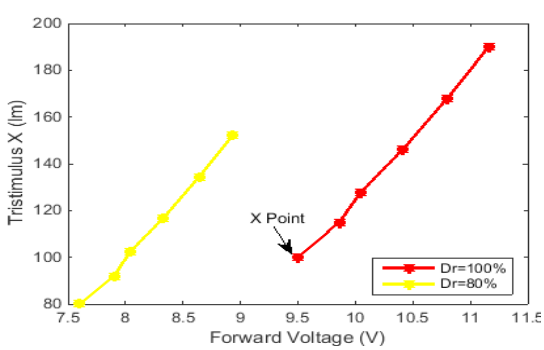
(b)



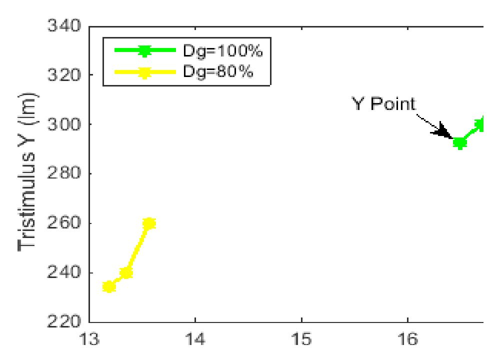
(c)

Figure 5: (a) V-I characteristics of Red (b) V-I characteristics of Blue (c) V-I characteristics of Green

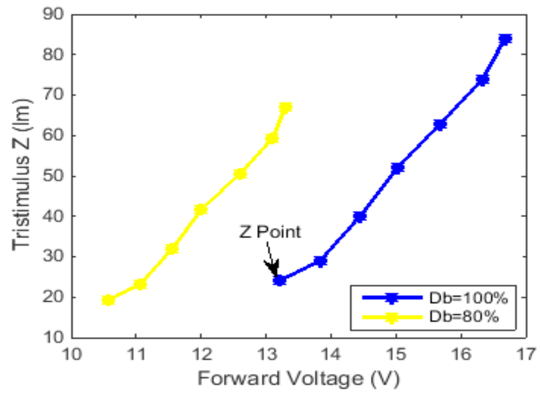
Thus the color point is linearly related to duty cycle which in turn is linearly related to current and forward voltage [3]. Sufficient time was given for the forward diode voltages to settle down before taking measurements. Thus if XYZ are temperature invariant and d is well controlled the light color output will be very stable.



(a)



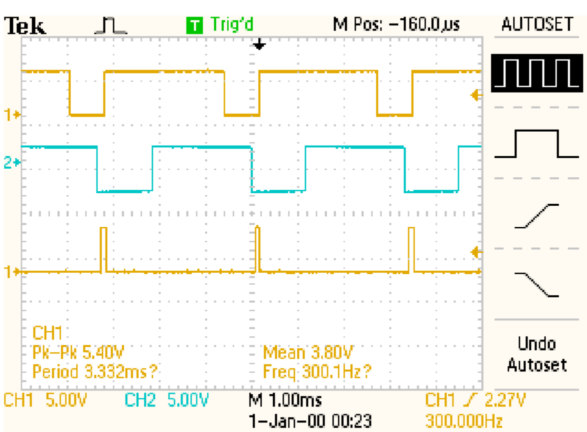
(b)



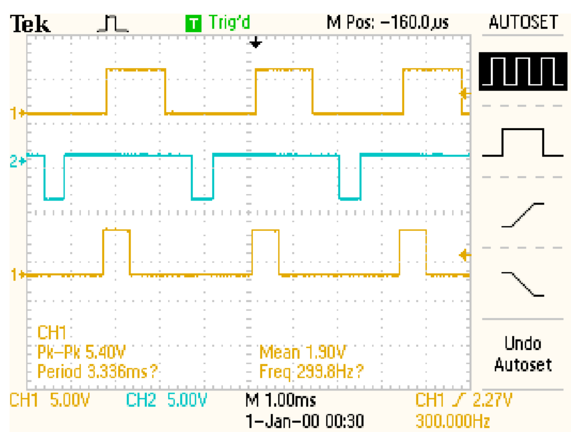
(c)

Figure 6: Plot of Forward voltage vs Tristimulus (X Y Z) for CCT = 6500K where (a) Graph of voltage vs X (b) Graph of voltage vs Y (c) Graph of voltage vs Z

The PWM signals generated by the DAQ system to obtain some CCTs are shown in figures 7 (a) – (d). The switching frequency was set to 300Hz to avoid flickering of LEDs. Similarly for all the 8 CCTs from 2700K-6500K different PWM signals were generated and that were used for generating white shades.



(a)



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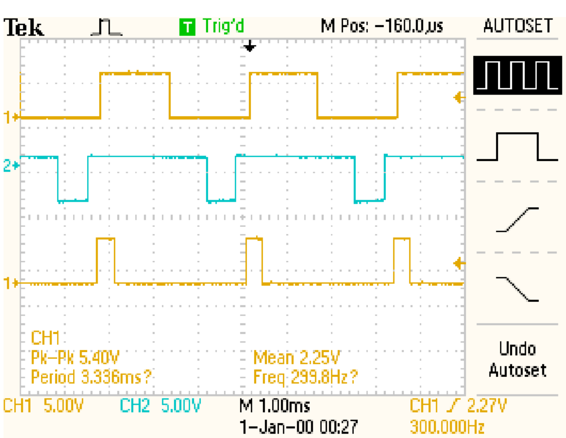

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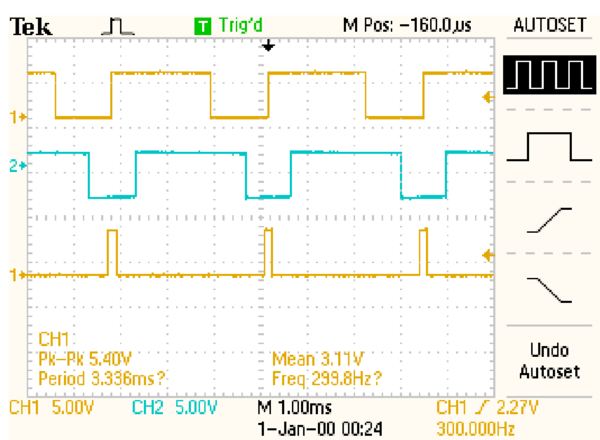
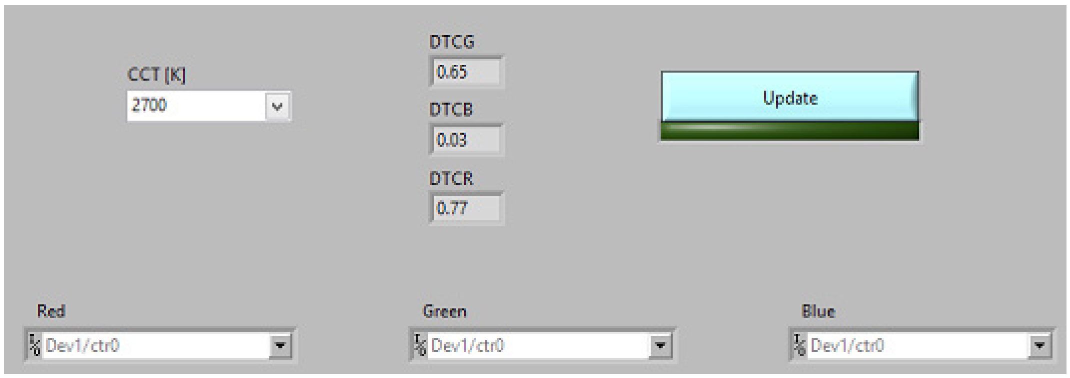


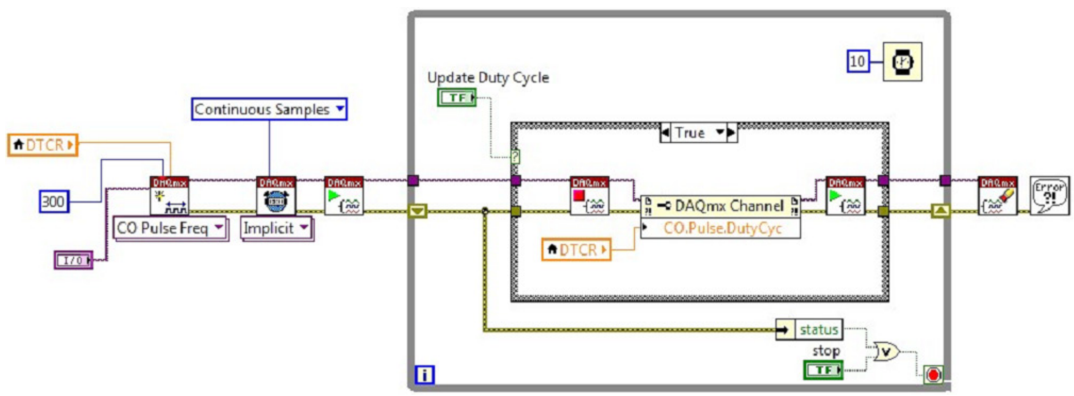
(d)

Figure 7: (a) PWM signals of RGB for 2700K (b) PWM signals of RGB for 3500K (c) PWM signals of RGB for 5000K (d) PWM signals of RGB for 6500K

A user interface is created on LabVIEW to get the desired CCT according to the user's needs and calculate the required dimming factors and send control signals to data acquisition system for generation of PWM. Figure 8 (a) shows the front panel and (b) shows the PWM generation block diagram of the created VI.



(a)



(b)

Figure 8: (a) Front Panel (b) PWM generation block

3.1 Experimental set-up:

The arrangement of RGB LEDs on the heat sink is shown in figure 9. Each RGB LED channel is separately driven by identical switching converters as shown in figure 11. National Instruments DAQ system was used for generating PWM and drive the three drivers. The experiments were performed inside humidity chamber to maintain Ta=25oC as shown in figure 10

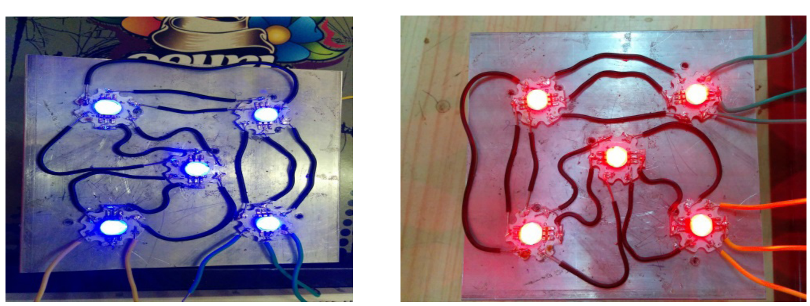


Figure 9: Red, Green and Blue LEDs @ 350 mA

Figure 10: Humidity chamber

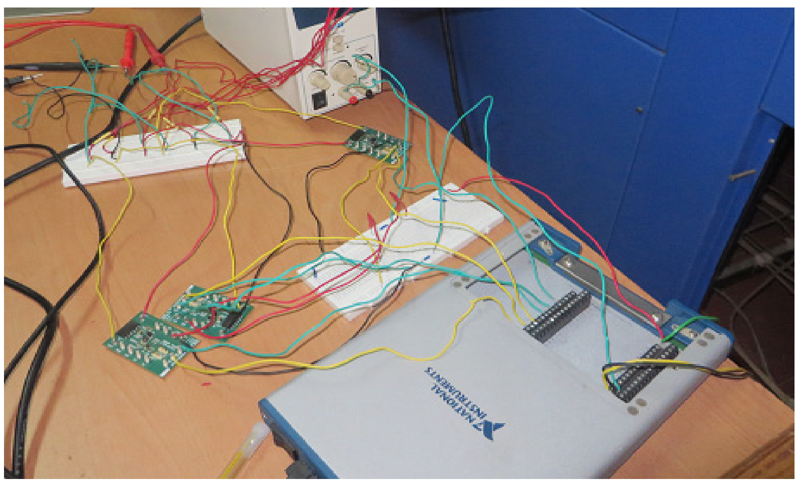


Figure 11: Drivers with NI DAQ

4. CONCLUSION

Color control is an important issue in the design and manufacture of LED lighting systems. The system developed is a user controlled tunable system that can produce different white shades of light according to the user requirement. The implementation technique has been outlined and verified by some experimental data. With the use of minimum and simple components the technique can effectively control the color point. The system can be further developed as a closed loop system to control the variation of color point due to junction and ambient temperature.

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