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Quantitative Analysis of Color Combination from LED and Laser Light Sources Using Modified CIE 1931 Color Space Coordinates

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Abstract. In this study, a quantitative analysis was conducted based on the CIE 1931 color space to determine a number of color combinations of three LED (light emitting diode) light sources and three laser sources respectively. The light sources used in this research were three LEDs that emitted blue, green and red light, and three laser sources that also emitted blue, green and red light. The results of the color combinations of these light sources were captured using a spectrophotometer. The obtained light spectra were then analyzed using a set of color matching functions that was modified specially for the spectrophotometer used. This research produced a quantitative analysis of 26 color combinations from LED light sources and 7 color combinations from laser light sources. The results of the color combinations ranged from blue, cyan, yellow, orange and red to purple. Further development of the proposed method is still required to obtain more reliable quantitative analysis results.

Keywords: *color combination; CIE 1931; lasers; light-emitting diodes.*

1 Introduction

Colorful light is a distinctive natural beauty that is beneficial to human life. Various methods can be used to create controllable lighting technologies. Some well-established lighting technologies are computer screens and mobile phones and outdoor bulletin boards using light emitting diodes (LEDs). The utilization of three types of LEDs that each emit a basic color, i.e. blue, green and red, can produce secondary and tertiary colors, covering almost all colors in everyday life [1,2]. Although the assessment of colors is still based on human feeling and senses, a quantitative analysis of light must use a quantitative analysis standard, such as the color space coordinates published by the Commission Internationale de l'Éclairage (CIE), from CIE 1931, CIE 1933 to CIE 1960 [3]. In this research, the CIE 1931 standard coordinates were modified to quantize color combinations from LED light sources and laser light sources. The selection of CIE 1931 was based on the fact that this color space is easy to understand by many users, is widely used to characterize colors of commercial LEDs, and

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describes colors as physiologically perceived in human vision. The standard method to use CIE color spaces is by utilizing a color matching function [4,5].

A problem that arises in the quantitative analysis of color is that a suitable color matching function is unavailable or that the standard color database is discrete and in some cases not in accordance with the resolution of the spectrophotometer used to record the light spectrum. Another problem arises when the recorded light spectrum is very sharp, such as the spectrum from a laser, in which case quantitative analysis using CIE color space coordinates cannot be applied because the results of the calculations will be incorrect if they refer to the visual appearance of the color produced. To solve these problems special development or modification of a color matching function is required to match a specific color spectrum with the color space coordinates. The purpose of this study was to modify the original data of a color matching function so that they could be applied to the recorded emission spectra using a spectrophotometer for both emission from the spectrum of LED light and the spectrum of laser light in order to produce a quantitative analysis of color combinations using the CIE 1931 color space coordinates. Quantitative analysis of color combinations from LED and laser light sources has been done previously, however, no standard color space coordinates were used to characterize the findings [6-8].

2 Experimental Method

To produce various color combinations three LED light sources and three laser light sources were used respectively and assembled as shown in Figure 1. The three LED light sources, emitting blue (wavelength of 460 nm), green (wavelength of 520 nm), and red (wavelength of 640 nm) light respectively, were arranged as in Figure 1(a). The LEDs used in this work were commercial LEDs that are easily obtained in the market. Each LED source was supplied a 3V DC electrical current that passed through a switch (S1, S2, and S3) and a resistor (R1, R2 and R3). The switch was used to switch off the input curent manually if only one or two LED light sources were required. Resistor R was used to adjust the current supplied to each LED source in order to obtain varied color combinations. By using the switches and the resistors approximately 26 color combinations from the three LED sources used were obtained. The emissions from the three LED sources were directed towards N-BK7 ground glass diffuser material to mix and combine the colors so that after passing through this diffuser material one new combined color was produced. The emission spectrum of each color combination was detected using a spectrophotometer via an optical fiber input. The spectrophotometer used was capable of detecting the light emission spectrum ranging from wavelength 350 nm to 750 nm with a slightly random wavelength interval of 0.25 nm. This wavelength interval is not uniform, since the wavelength interval is determined by embedded grating and the array detector inside the spectrophotometer. This irreguler interval is one of the problems that will be discussed in the next section.

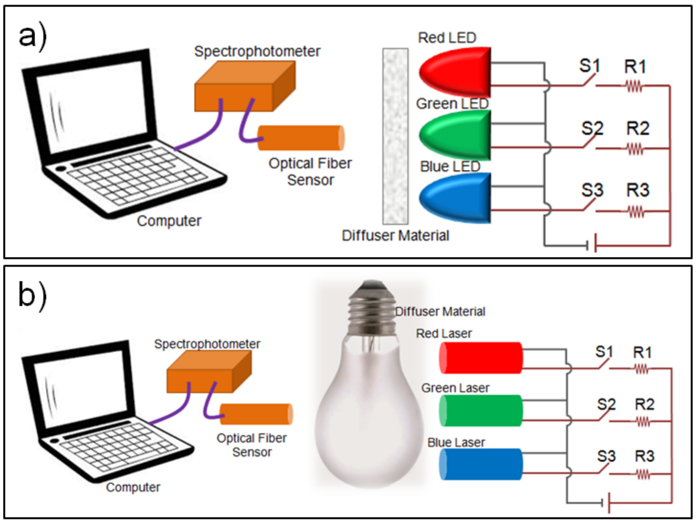

Figure 1 Experimental setup to obtain color combinations from (a) LED light sources and (b) laser light sources.

In addition to the LED light sources, color combinations were also obtained by using three laser light sources, emitting blue (wavelength of 405 nm), green (wavelength of 532 nm), and red (wavelength of 650 nm) color respectively, as shown in Figure 1(b). The three laser light sources were commercial laser pointers that are usually used as presentation tools and are easily obtained in the market. The electronic arrangement and capture of the light emission spectrum were similar to those used in the experimental setup for the LED sources. In this setup, however, the white light of an incandescent light bulb was used as the diffuser material in order to create the new color combinations. Due to the limitations of the electric current used, only seven color combinations were obtained. These limitations were due to the injection current threshold for lasers, which is higher than that for LEDs.

The light emission spectra were recorded using a spectrophotometer from Ocean Optics HR2000. Each recorded light emission spectrum describes a color combination, which is a new secondary or tertiary color. The colors can be identified by the human eye. In this research, in order to analyze the colors a color matching function (x_λ,y_λ,z_λ) database was applied to the color emission spectrum using the following simplified equations.

$$X = \sum_{\lambda=\lambda_{blue}}^{\lambda=\lambda_{red}} x_\lambda I_\lambda \tag{1}$$

$$Y = \sum_{\lambda=\lambda_{blue}}^{\lambda=\lambda_{red}} y_\lambda I_\lambda \tag{2}$$

$$Z = \sum_{\lambda=\lambda_{blue}}^{\lambda=\lambda_{red}} z_\lambda I_\lambda \tag{3}$$

The CIE 1931 color space coordinates are obtained using the following equations.

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

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

$x_\lambda, y_\lambda, z_\lambda$ are the values of the color matching function, I_λ is the spectrum intensity at specific wavelength (λ), and x, y is the resulting CIE 1931 color space coordinate. The value of x and y is then plotted on the CIE 1931 color diagram. In Eqs. (1)-(3), X, Y and Z are the sum of the emission intensity at certain wavelength times and its corresponding color matching function. In this case, X, Y and Z do not have a specific unit since they are only a summation of intensity.

3 Result and Discussion

Based on the experimental setup as shown in Figure 1, the color combinations of LED sources and laser sources were obtained as shown in Figure 2. In this experiment, 26 color combinations were obtained from three LED light sources. The three basic colors of the LED sources that were used in this experiment are shown visually in Figure 2(a-c) for the LED sources emitting red, green and blue light, respectively. Various colors were obtained by combining two or three LED light sources with different levels of LED light intensity. The resulting colors ranged from blue, cyan, green, orange, red to purple. These new colors were obtained in front of the diffuser material. In this paper only a limited number of spectra and images of color combinations are presented due to the difficulty of camera visualization and technical problems in the electronic circuit control. Although only a few images and spectra are shown, the color combinations can produce the various colors as shown in the CIE 1931 color space diagram described later.

For the colors produced by combining laser light sources, the surface of an incandescent lamp was used as the diffuser material. This setup was slightly different from the setup for the LED light sources. In order to obtain a clear visual appearance of each color combination, the laser sources and diffuser material were placed inside a white-wall box so the new color could be easily identified by the naked eye. The use of a white-wall box did not disturb the recorded emission spectra of the color combinations since the light emission spectra were obtained directly from the surface of the bulb. Only 7 color combinations from the laser sources were obtained due to the limitations of the injection current used and the high injection current threshold of the laser sources. Three images showing color combinations produced using the three laser sources are shown in Figure 2(d-f), i.e. orange, cyan and purple, respectively.

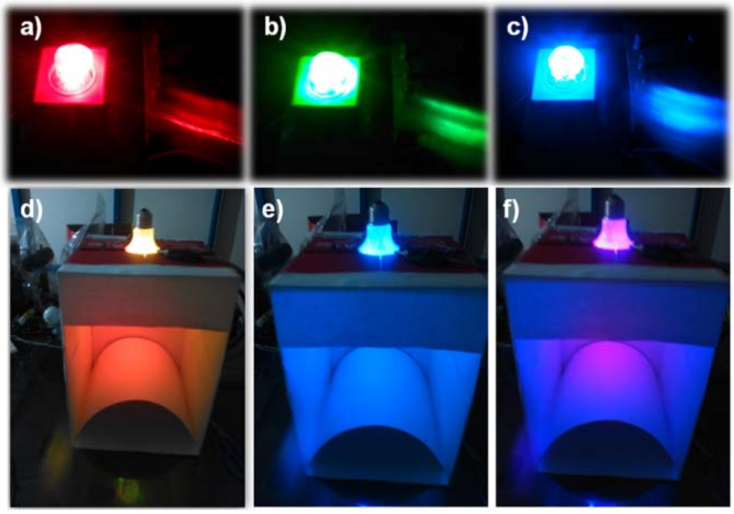

Figure 2 Photographs of LED light source emitting color: (a) red, (b) green and (c) blue, and color combination colors obtained from laser light sources: (d) orange, (e) cyan and (f) purple.

One of the problems that arise when analyzing the light emission spectrum of a new color combination is that the wavelength resolution of the detected spectra and the wavelength interval of the spectra are not the same as the resolution and the interval wavelength in the color matching function database. According to the literature of the color matching function, the wavelength interval is only 1 nm. However, the wavelength resolution and the wavelength interval of the spectrophotometer are slightly irregular (between 0.2 and 0.25 nm). This problem restricts the quantitative analysis, especially when Eqs. (1-3) and Eqs. (4-5) are applied. Therefore, a special treatment of the color matching function database is required. In order to adjust this condition, linear interpolation of the color matching function by considering the wavelength resolution and the wavelength interval of the spectrophotometer was applied. The curves of the color matching function and the interpolated color matching function can be seen in Figure 3. As shown in Figure 3(b), the curve of the interpolation is almost identical to the curve of the original color matching function database. This result ensures that the quantitative analysis is able to produce precise and accurate values. The values of the color space coordinates obtained were plotted in a CIE 1931 color diagram.

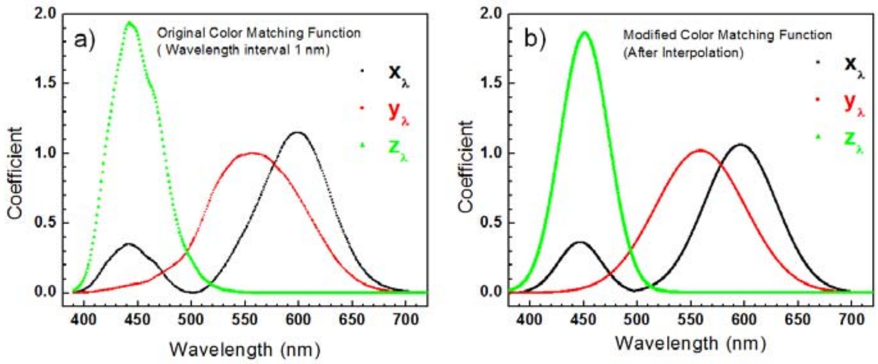

Figure 3 Curves of color matching function from (a) original database and (b) interpolated data.

Some examples of the light emission spectra of the color combinations of LED sources and laser sources can be seen in Figure 4. From the spectra of the color combinations of the LED light sources, it can be seen that the spectrum width of each color (blue, green and red) is quite wide (from 20 nm to 30 nm). Eqs. (1)-(5) were used to analyze the color combinations, along with the color matching function value that was interpolated as mentioned above. Visually, each color combination can be confirmed by placing the value from the quantitative analysis in the CIE 1931 color diagram, as shown in Figure 5. In general, it takes at least two color sources to generate a new color combination. For example, in Figure 4(a), spectrum no. 15 is a combination of blue LED and red LED light. Visually, this combination produces a purple color. Based on the quantitative analysis using our modified color matching function, the obtained position coordinates of the color space are at coordinates x = 0.35 and y = 0.13. The position of the purple color obtained from our analysis can be seen in the CIE 1931 color diagram at point no. 15 in Figure 5(a). The position of this color point clearly shows a purple color. Other examples of color spectra and color positions in the color diagram can be found in Figures 4(a) and 5(a), for spectrum no. 4, 6 and 9. Figure 5(a) shows 22 color positions of color combinations from three LED light sources. The distribution of color space coordinates proves that combinations of three colors from LED light sources are able to create a wide range of colors that can be detected by the human eye. Moreover, a three-color combination of LED light sources is able to produce a white color, as shown by the light emission spectrum in Figure 4(a) and Figure 5(a), point no. 9. The combination of the three LED light sources is nearly balanced to produce the color white. Therefore, by using the interpolated color matching function, all light emission spectra of the color combinations of the LED light sources could be analyzed properly.

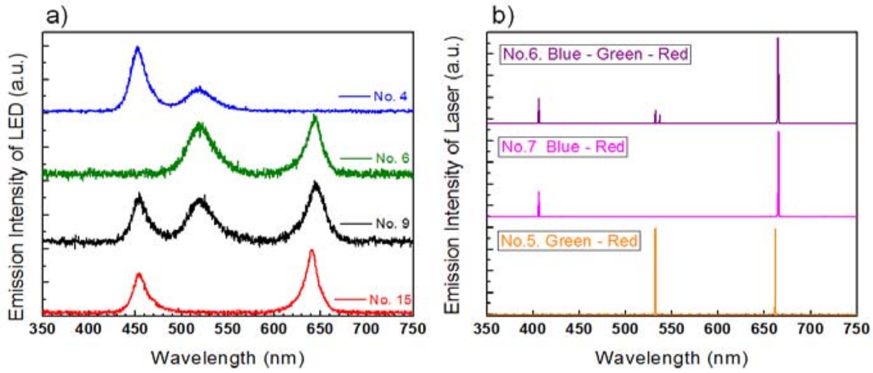

Figure 4 Emission spectra of color combinations from (a) LED light sources and (b) laser light sources.

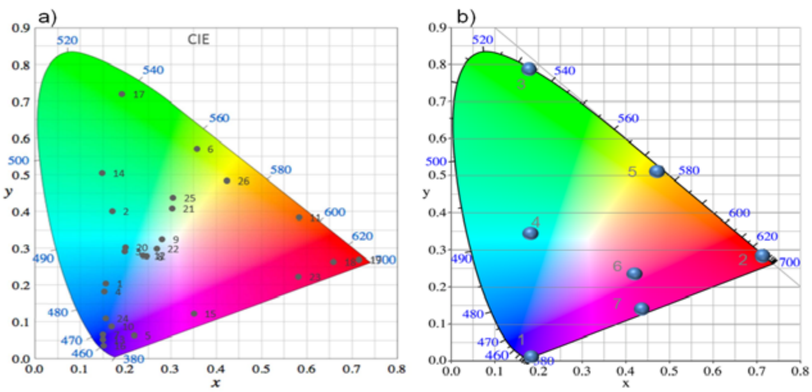

Figure 5 Diagram of coordinates of CIE 1931 color space for color combinations from (a) LED light sources and (b) laser light sources.

Unlike the emission of LED light sources, the emission of laser sources has a very sharp and narrow spectrum since, ideally, each laser source emits only one particular wavelength. However, due to the limitations of the equipment and detectors, the laser light sources in this experiment had a spectrum width of 1 to 2 nm. Visually, combinations of laser light sources can generate new colors.

However, a problem arises when quantitative analysis is done using the color matching function for Eqs. (1) and (2). The values of the generated CIE 1931 space coordinates do not match visual observation. Therefore, a different approach is required to analyze the spectra of combinations of laser light sources. In this research, only three wavelengths, corresponding to laser light sources (460 nm, 532 nm and 650 nm), were used. To obtain a new color matching function for these three wavelengths, a standard color point in the CIE 1931 color diagram was used for each laser source. From the calculation results, the values of the color matching function for the three wavelengths were obtained as shown in Table 1.

Table 1 Values of color matching function for color combinations from laser light sources.

No	Laser wavelength (nm)	Value of Color Matching Function		
		x_λ	y_λ	z_λ
1	405	0.15	0.01	0.65
2	532	0.11	0.48	0.02
3	650	0.53	0.21	0

Using the color matching function in Table 1, quantitative analysis of the emission spectra from the laser light sources was done using Eq. (1) and Eq. (2). The calculated color space coordinates were then plotted in the CIE 1931 color diagram. For example, in Figure 4(b) spectrum no. 6 has three laser peaks, i.e. blue, green and red. The values of the CIE 1931 color space coordinate results from the analysis can be seen in Figure 5(b), point no. 6. Visually, the combination of the three laser sources produced a slight purple color, since the red emission was stronger than the blue and the green. Several other color combinations of laser light sources can be seen in Figures 4(b) and 5(b). In general, the color combination spectra from laser light sources can be well analyzed using only three wavelength color matching functions. However, better calculation is required to determine the best value of the color matching function, especially for the three wavelengths that were used.

4 Conclusion

Color combinations from LED and laser light sources are able generate new colors by combining three primary colors, i.e. blue, green and red. In the present research, 26 new color combinations by using LED light sources and 7 new color combinations by using laser light sources were obtained. Quantitative analysis of the color combinations from the LED light sources was done using an interpolated color matching function. Furthermore, quantitative analysis of the color combinations from the laser light sources was done using a modified three-wavelength color matching function. Quantitative analysis of the colors combinations from the LED light sources and laser light sources was successfully conducted. The color space coordinates could be well plotted in the CIE 1931 color diagram. Further research is required to improve the color matching function in order to get a more reliable quantitative analysis of color combinations, including verification of this analysis through a series of surveys involving several people in order to justify and clarify the colors produced by the laser and LED combinations.

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