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Prototyping of low-cost color enhancement lighting using multicolor LEDs

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Abstract

We used low-cost multicolor LEDs to prototype a lighting system for color enhancement with white appearance maintained. We bought LEDs of several colors at local electronic parts shops, and evaluated their spectral power distributions for synthesizing lights for illumination. Five LEDs were chosen for natural color observation of the object, and three of them were used for color enhancement. Experiments conducted using the assembled LED lighting system and a color chart showed that reddish and blueish color patches were enhanced with white appearance chromatically maintained.

Introduction

Illumination for enhancing the color of target objects are required in the medical field and food retail industry for enhancing an observer's impression or attracting an observer's attention, and several methods for optimizing the spectral power distribution (SPD) of illumination have been proposed [1-4]. Some of them have been implemented using a multicolor LED lighting system. However, all of them used expensive lighting systems. Low-cost lighting is required for generalizing these methods.

Our goal is to develop an electric torch that can switch its lighting for observing natural color and enhanced color. This paper presents our prototype, assembled using LEDs of five colors bought at local electronic parts shops. All five LEDs were used for observing natural color, and three of them were used for color enhancement. The color appearance of white was maintained in both lighting modes.

The following section describes the method to determine combinations of multicolor LEDs for observing natural color and enhanced color. Experimental results evaluate color enhancement effects on a CIE Lab color space using a color chart.

Design of spectral power distribution of illumination

First, the intensity of each color for observing the same colors under a reference illumination is determined as follows. Let $\mathbf{x} = [x_{380}, \cdots x_{780}]^T \in \mathbb{R}^{401}$ be an SPD of illumination synthesized by LEDs. When $\mathbf{x}$ can be modeled as a linear combination of the SPD of LEDs, $\mathbf{n}_k$, $\mathbf{x}$ is represented as

$$\mathbf{x} = \sum_{k=1}^{N} \alpha_k \mathbf{n}_k, \tag{1}$$

where α_k and N represent the intensity parameters of each LED and the number of LEDs, respectively. $\mathbf{x}$ is determined by finding α_k for all LEDs. Let $\mathbf{C}_X, \mathbf{C}_Y$, and $\mathbf{C}_Z \in \mathbb{R}^{401}$ be CIE color matching functions for *X*, *Y*, and *Z*, respectively, $\mathbf{w} = [w_{380}, \cdots w_{780}]^T \in \mathbb{R}^{401}$ be the SPD of reference illumination, $\mathbf{R}_t = \mathrm{diag}(\mathbf{r}_t)$ be the spectral reflectance of the *t*th object's color. The SPD of illumination for observing natural colors is obtained by finding $\mathbf{x}$ that minimizes the root mean squared error (RMSE) between $\mathbf{w}$ which has the same CIE Y, u', and v' values. This can be represented as

$$\begin{aligned} &\underset{\mathbf{x}}{minimize}\ \left\{\sum_{k=380}^{780}(w_k - x_k)^2\right\}^{1/2}, \\ &\text{s.t. } \{(\delta \mathrm{u}'_{white})^2 + (\delta \mathrm{v}'_{white})^2\}^{1/2} < 0.004, \\ &\qquad \delta \mathrm{Y}_{white} = \|\mathbf{C_Y R}_{white}\mathbf{w} - \mathbf{C_Y R}_{white}\mathbf{x}\| = 0, \end{aligned} \tag{2}$$

where

$$\delta \mathrm{u}'_{white} = \|U'(\mathbf{CR}_{white}\mathbf{w}) - U'(\mathbf{CR}_{white}\mathbf{x})\|,$$
$$\delta \mathrm{v}'_{white} = \|V'(\mathbf{CR}_{white}\mathbf{w}) - V'(\mathbf{CR}_{white}\mathbf{x})\|.$$

$U'(\ )$ and $V'(\ )$ represent operators for calculating CIE u' and v', and $\mathbf{C} = [\mathbf{C}_X, \mathbf{C}_Y, \mathbf{C}_Z]^T$.

Next, let us consider the case where red, green, and blue are enhanced at the same time [3]. The illumination $\mathbf{x}$ satisfying the following equation is calculated:

$$\begin{aligned} \underset{\mathbf{x}}{maximize}\ \{&\|L(\mathbf{CR}_{\boldsymbol{blue}}\mathbf{w}) - L(\mathbf{CR}_{\boldsymbol{blue}}\mathbf{x})\| \\ &+\|L(\mathbf{CR}_{\boldsymbol{green}}\mathbf{w}) - L(\mathbf{CR}_{\boldsymbol{green}}\mathbf{x})\| \\ &+\|L(\mathbf{CR}_{\boldsymbol{red}}\mathbf{w}) - L(\mathbf{CR}_{\boldsymbol{red}}\mathbf{x})\|\}, \\ \text{s.t. } &\|L(\mathbf{C}\mathrm{R}_{red}\mathbf{w})\| < \|L(\mathbf{C}\mathrm{R}_{red}\mathbf{x})\|, \\ &\|L(\mathbf{C}\mathrm{R}_{green}\mathbf{w})\| < \|L(\mathbf{C}\mathrm{R}_{green}\mathbf{x})\|, \\ &\|L(\mathbf{C}\mathrm{R}_{blue}\mathbf{w})\| < \|L(\mathbf{C}\mathrm{R}_{blue}\mathbf{x})\|, \end{aligned} \tag{3}$$

where $L(\ )$ is an operator for calculating CIE a^*b^* values of a given spectrum and $\|L(\ )\|$ is an operator for calculating $\{(a^*)^2 + (b^*)^2\}^{1/2}$.

Experiments

Selection of LEDs

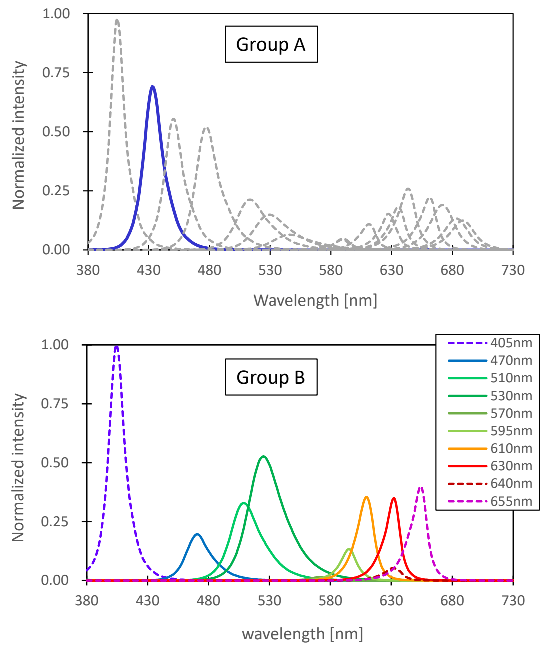

Figure 1. SPDs of LEDs.

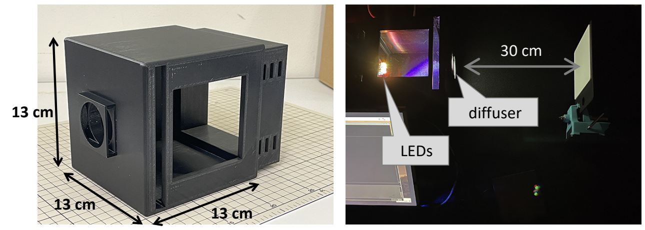

Figure 2. Case for prototyped electronic torch and its experimental

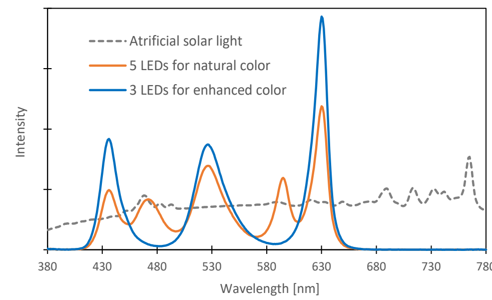

Figure 3. SPDs of artificial solar light and synthesized illuminations.

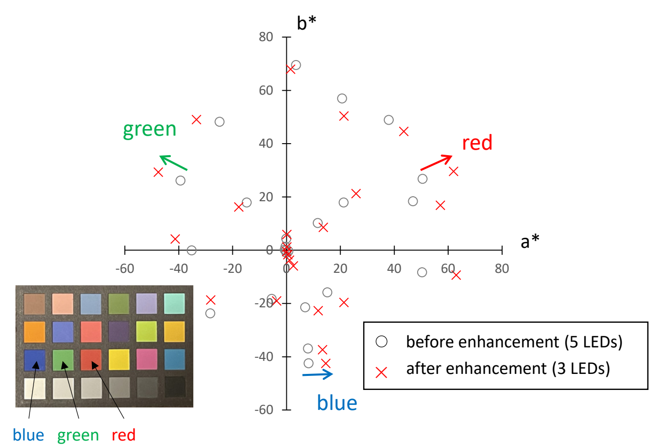

*Figure 4. Color of each patch plotted on CIE a*b* color plane.*

Figure 1 shows twenty-nine SPDs of the LEDs we bought in at local electronic parts shops. Every LED has a bullet-shaped lens. The average price of group A (REVOX Inc.) and group B (unknown makers) were 5 USD/piece and 0.15 USD/piece, respectively. The LEDs in group B are preferred in terms of bringing down the cost. However, in group B, LEDs whose center wavelength ranges from 400 to 450 nm, i.e., deep blueish color, were unavailable. Therefore, a LED in group A whose center wavelength is 435 was included in the options. LEDs whose center wavelengths were 405 and 665 nm in group B were removed from the options because the human eye has relatively lower sensitivity for these wavelengths, and these LEDs might discourage the smoothness of the SPD of synthesized light when the number of LED colors is limited. The LED whose center wavelength is 570 nm was much darker than others. Moreover, SPDs of LEDs whose center wavelengths were 510 and 530 nm have a large overlap, which makes few enhancement effects for greenish colors. For the reasons stated above, we built the prototyped electric torch using the following five color LEDs: 435, 470, 530, 610, and 630 nm.

Let us consider the case where five color LEDs are used for color saturation control, two for blue, one for green, and two for red. When reddish colors are enhanced, the red LED with a longer center wavelength is brightened, and the red LED with a shorter one is darkened. In the case of muting red, the opposite operation is conducted. This enables us to enhance or mute reddish color while maintaining the appearance of white. Bluish colors are also controlled based on the same idea. The green LED was used for maintaining the appearance of white.

Prototype of electric torch

A case measuring 13 x 13 x 13 cm was shaped for the electronic torch using a 3D printer (F120, Stratasys Ltd.). A diffuser was attached to its exit window. Figure 2 shows the case and experimental setup. The distance between the diffuser and a standard white was 30 cm. The brightness of the LEDs was controlled by pulse-width modulation (PWM) using Raspberry Pi. PWM can avoid variations of the center wavelength of LEDs that occur in the case of current modulation.

Chromaticity evaluations of color enhancement effects

An artificial solar light (XELIOS, SERIC Ltd.) was used as a reference illumination. Figure 3 shows SPDs of the light (gray dashed line), the synthesized light using five color LEDs for observing natural colors (solid orange line), and the synthesized light using three color LEDs for observing enhanced color (solid blue line). The color difference of white on the CIE u'v' color space was 0.004, which satisfied the requirement described in Eq. (2). Color patches on the GretagMacbeth Mini ColorChecker™ were used for SPD optimization and evaluation of color enhancement effects.

Figure 4 shows the results of the color enhancement. The color of each patch is plotted on the CIE a*b* color plane.

Variations of red, green, and blue patches on the color plane were 11.8, 8.8, and 6.4, respectively. These results show that the experiments succeeded in enhancing color while maintaining the appearance of white.

Summary

We prototyped an electric torch that can switch its lighting for observing natural color and enhanced color. The color appearance of white could be maintained in both lighting modes. The torch consisted of five color LEDs, and we showed its ability experimentally. The combination of LEDs was optimized for enhancing red, green, and blue simultaneously as in previous work [3]. As future work, we are planning to optimize the SPDs of illumination for some specific applications, such as the detection of extraneous material in the food manufacturing industry or in the medical field, and assess their effects experimentally.

References

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Author Biographies

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