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Quadratic Color Model and Color Generation using RGB LEDs and Simplex Search Method

For Industrial Lighting Control

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***Abstract*—A method for generating the target color in industrial lighting systems was proposed using the quadratic color model and simplex search method. The target color can be set in a Windows-based system and converted into the XYZ color coordinate system from the sRGB space. A quadratic color model was constructed between the input levels of RGB LEDs and the color coordinates of individual light components in a mixed light source. The quadratic color model is used to cover errors under low luminance condition while using the linear color model. The input levels were determined using the target color and quadratic model. In this study, the simplex search method is applied for determining input levels and is compared with other conventional methods.**

***Keywords*—color control, mixed light source, Chromaticity, automatic lighting, active illumination, simplex search**

I. Introduction

Industrial lights help in improving the discriminability of products and the working efficiency of manufacturing lines. During quality inspection of products for quality control, damages and faults can easily be detected using specific color lighting. The performance of machine vision systems is also affected by the light wavelength, which is related to the light color.[1],[2] As the light color of an LED can affect the circadian rhythms of factory workers, the selection and generation of optimal light color play an important role in LED applications.[3] Most industrial processes use single-colored lights; however, a mixed light source can also be used, as it can generate lights of various colors. The mixed light source comprises RGB LEDs, and light of target color is generated by varying the LED inputs.[4] Lights from different LEDs can be combined into light of a specific color by using a collimator [5], Esparza's light pipe [6], micro-lens array [7], tunable lamp [8] and shell mixer [9].

Color mixing techniques that are developed to generate solar-white light [4] have been employed to generate arbitrary colors. Target color can be defined on various color coordinates, such as RGB, HSL, CIE and color temperature.[10] The additive color model and linear summation are commonly used for modeling a mixed light source and Sisto proposed a generalized method for modeling a mixed light source.[11],[12],[13] Commercial driving ICs for RGB LEDs that generates a target color are based on this model.[14],[15] Many studies on light mixing begin with the assumption that RGB LEDs comprise lights having pure colors; however, commercial LEDs emit RGB lights and have an optical offset under low luminance condition. The other problem is determining the input levels of RGB LEDs for generating a target color.

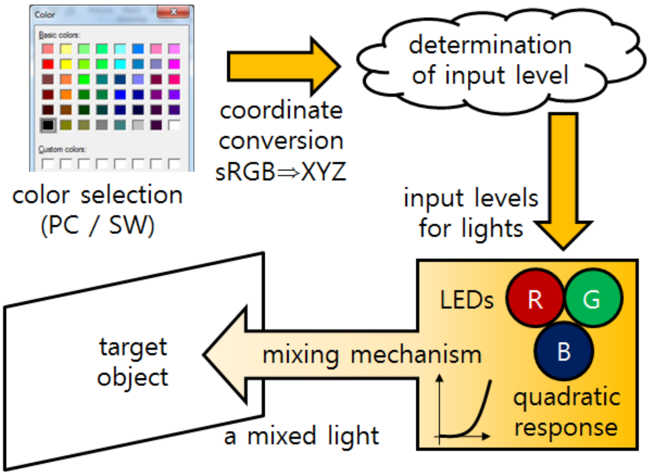

Figure 1. Conceptual diagram of color selection and generation

Considering that commercial RGB LEDs comprise lights of impure colors, for pure color generation, input levels must be determined for reproducing the light color closest to the target color. Although Sisto's method has already taken problems into consideration, the optimum search teqchnique is iterative, and the linear model generates a large error under low luminance condition. Therefore, this study used a quadratic model of the mixed light source and the simplex search method (SSM) to determine the input levels in a short time. An experiment was performed with the proposed algorithm using machine vision.

II. Light Mixing Algorithm

A. *Additive and Quadratic Color Model*

The target color can be chosen from a color selection dialog box in Windows^{TM} Wordpad, as shown in Figure 1. After the desired color is selected by clicking on it, its RGB or HSL values are obtained. In PCs, the RGB coordinates are usually expressed as sRGB and can be converted into various color spaces. Equation (1) shows the coordinate conversion from RGB to XYZ. [16]

$$\begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix} = c \begin{bmatrix} 0.5767 & 0.1865 & 0.1882 \\ 0.2974 & 0.6273 & 0.0753 \\ 0.0270 & 0.0707 & 0.9911 \end{bmatrix} \begin{pmatrix} R_0 \\ G_0 \\ B_0 \end{pmatrix} \qquad (1)$$

If the sRGB and XYZ spaces have different scales, a scaler factor c must be defined. In PCs, the RGB space has 8-bit levels; however, a mixed light source usually has a higher bit level. Commercial RGB LEDs have tri-stimulus values, even if they are pure color RGB LEDs. The color intensity of an LED light is proportional to the input level, which can be represented using generalized coordinates, P and Q. Hence, the linearity and input levels for a red LED can be written as follows:

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$$\begin{pmatrix} p_X \\ p_Y \\ P_Z \end{pmatrix} = \begin{pmatrix} a_{RX} q_R \\ a_{RY} q_R \\ a_{RZ} q_R \end{pmatrix} \tag{2}$$

However, commercial LEDs have offset luminance, almost equal to zero, and constants must be added, as shown in the (3).

$$\begin{pmatrix} p_X \\ p_Y \\ P_Z \end{pmatrix} = \begin{pmatrix} a_{RX} q_R + b_{RX} \\ a_{RY} q_R + b_{RY} \\ a_{RZ} q_R + b_{RZ} \end{pmatrix} \tag{3}$$

A quadratic model can be derived from (3) as follows:

$$\begin{pmatrix} p_X \\ p_Y \\ P_Z \end{pmatrix} = \begin{pmatrix} a_{RX} q_R^2 + b_{RX} q_R + c_{RX} \\ a_{RY} q_R^2 + b_{RY} q_R + c_{RY} \\ a_{RZ} q_R^2 + b_{RZ} q_R + c_{RZ} \end{pmatrix} \tag{4}$$

A general form of the input level and intensity of the generated color can be defined as follows:

$$p_i = a_{ji} q_j^2 + b_{ji} q_j + c_{ji} \tag{5}$$

where i is one of the XYZ color coordinates, and j is one of the RGB LEDs. If the RGB LEDs are driven simultaneously, the color responses of the linear and the quadratic expression can be calculated as follows:

$$p_i = \sum_{j}^{R,G,B} \left(a_{ji} q_j + b_{ji} \right) \tag{6}$$

$$p_i = \sum_{j}^{R,G,B} \left(a_{ji} q_j^2 + b_{ji} q_j + c_{ji} \right) \tag{7}$$

Equations (6) and (7) can be written in matrix form as follows:

$$P = Q^T A + B \tag{8}$$

$$P = diag(QQ^T)A + Q^T B + C \tag{9}$$

The generated and the target colors must be the same; thus the RGB in (1) and P are considered as follows.

$$P = P_0 = cM \cdot (R_0, G_0, B_0) \tag{10}$$

Although equation (8) can be solved using an inverse matrix A^{-1}, the exact solution can be deviated from physical conditions, because q_j cannot take negative values, which often occur when the target color is pure. The mathematical operation of finding the inverse of a matrix can be unstable; equation (9) can instead be solved using numerical methods. A previous study considered equal step search, which required many iterations and a long processing time. Thus, the SSM was considered and applied to determine Q.

B. *Simplex Search Method*

The SSM forms a geometrical probing network composed of n+1 points and transforms the shape of the probing network with respect to the minimum point. The coordinates of the points are defined using Q. For three input problems, the shape of the simplex is a tetrahedron. The SSM was applied to find the optimal light color for machine vision systems.[17],[18] The transformations involved are expansion, contraction, and shrinkage, as shown in Figure 2.[19] A cost function is an index for determining the minimum, and should be defined as common optimum methods.

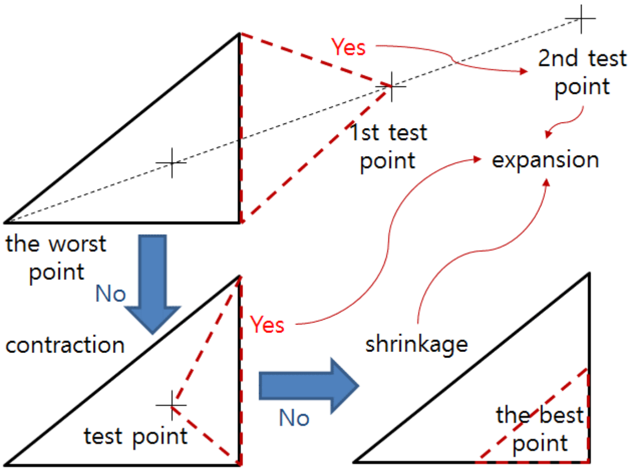

Figure 2. Transformations by simplex using SSM

$$\min_f f = E^T \cdot E \tag{11}$$

where E is the difference or distance between the target and generated colors in the XYZ color coordinate system, and E^T be written as follows:

$$E^T = (X_0 - X, Y_0 - Y, Z_0 - Z) = P_0 - P \tag{12}$$

Therefore, the index is evaluated using the cost function and the current values of Q. The best and worst points in the simplex can be determined using the cost function. Expansion is attempted on the first test point in an extension line. The extension line is formed by joining the worst point to the centroid. The first test point is placed at the same distance outside the simplex as that of the median on the extension line. If the first test point is the new minimum, the second test point is defined outside the first test point at the same distance as that of the median on the extension line. Then, the worst point is replaced by one of these two points. If the first test point is not the new minimum, the second test point is defined on the centroid. If the second test point is the new minimum, the worst point is changed to the second test point. If the new minimum is still not found, the simplex is shrunk towards the best point. These transformations are iterated until the size of simplex becomes considerably small.[20]

The color coordinate P, which was found using the simplex method, can be applied to check the color coordinates of generated light. As it is difficult to plot XYZ color coordinates in a 2D space, they can be converted to CIE1931 xyY coordinates. The conversion can easily be made using the following equation:

$$(x, y, Y) = \left(\frac{p_1}{\sum p}, \frac{p_2}{\sum p}, p_2 \right) \tag{13}$$

III. Experiment and Results

A. *Test System and Procedure*

A test system was constructed using commercial machine vision devices. The target color was selected by choosing a color from the color selection dialog box in Windows™ Wordpad, and an 8-bit RGB coordinate was obtained. A mixed light source can generate RGBW light simultaneously with high-power LEDs (KLS-150, Kwangwoo).

TABLE I. CORRELATIONS OF LINEAR AND QUADRATIC MODELS

Model	LED Color	R^2 obtained from measured color coordinate		
		X	*Y*	*Z*
Linear	R	1.0000	1.0000	0.8268
	G	0.9987	0.9999	0.9929
	B	0.9995	0.9995	0.9995
Quadratic	R	1.0000	1.0000	0.8270
	G	0.9991	0.9987	0.9997
	B	0.9993	0.9993	0.9994

The input of the mixed light source can be transferred through the RS-232C interface and has 11-bit levels. The mixed light was transferred to a coaxial lens (COAX, Edmund) for semiconductor inspection, by using an optical fiber cable and an illuminated target object.

The color coordinate of the target object was acquired using a chroma meter (CL-200A, Konica-Minolta). The XYZ color coordinates were measured in the full range of individual RGB LEDs to check for linearity and quadrativity. Then, the coefficients of a, b, c and correlation R^2 were calculated from the measured XYZ; the R^2 of linear and quadratic models is shown in Table I. The linearity between the input level and the XYZ color coordinate was considerably good because the R^2 is almost close to 1.0.

B. *Results and Discussion*

The input levels of the RGB LEDs determined using the SSM satisfied the boundary conditions, whereas those determined using an inverse matrix, as in (8), showed negative values, which were outside the RGB range. The variations in the XYZ color coordinate were converted to the CIE1931 coordinate to assess their difference from the target color. The difference in CIE 1931 coordinates, (Δu, Δv), were observed for red, cyan, and white levels, as shown in Figures 3-5. For pure color tracking, the quadratic model was followed more accurately compared to other models. The linear model with the SSM showed similar characteristics as that of the quadratic model. Although the quadratic model generated a large error under a low luminance of less than 15% (red dotted lines in the figures), it reproduced the light color that was closest to the target light color. Our proposed method showed the least error compared to the other methods, except under the low luminance condition. Figures 6-8 shows that the luminance varied with the target color level. For pure colors, an inverse model always showed the offset, and an additional model showed the highest intensity, which indicated energy loss. The results obtained using the SSM followed the intensity contour of the target color. Hence, the SSM assisted in reducing the electrical energy required to generate a specific color. Moreover, the color coordinate was more accurate compared to that in other conventional methods. Others color also showed similar characteristics in the CIE1931 coordinate system.

IV. Conclusion

A quadratic model for a mixed light source and the SSM for input level determination were proposed for generating a target color accurately.

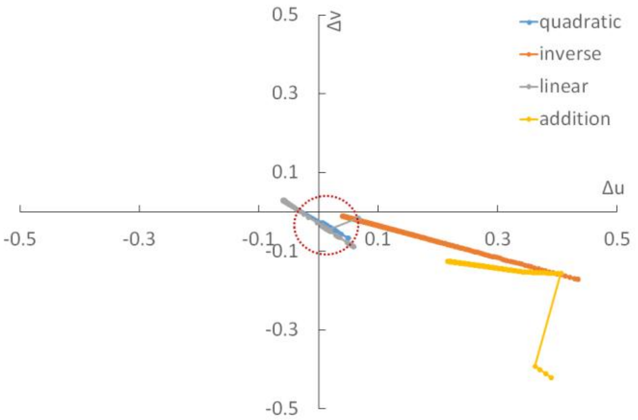

Figure 3. Color deviation on CIE1931 coordinate from targeting color red

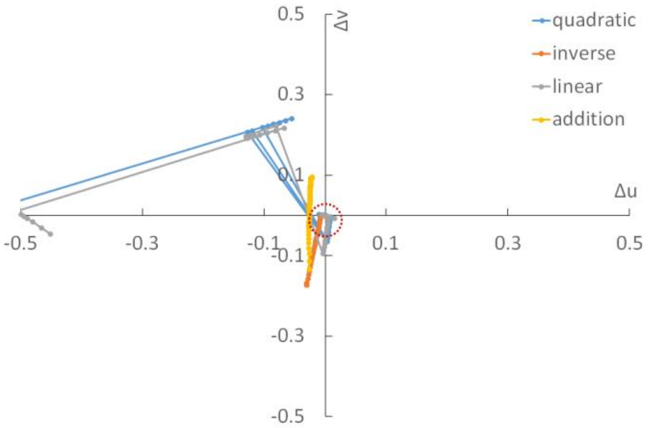

Figure 4. Color deviation on CIE1931 coordinate from targeting color cyan

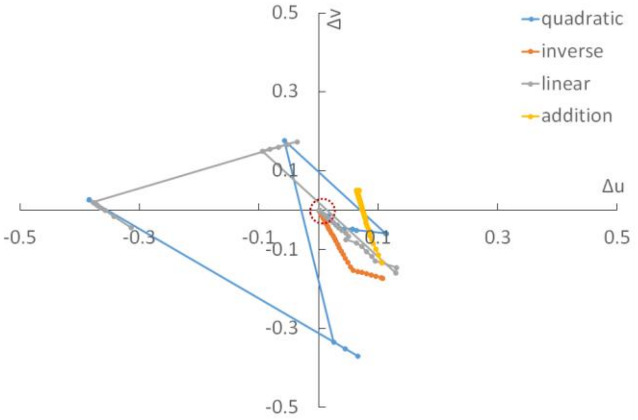

Figure 5. Color deviation on CIE1931 coordinate from targeting color white

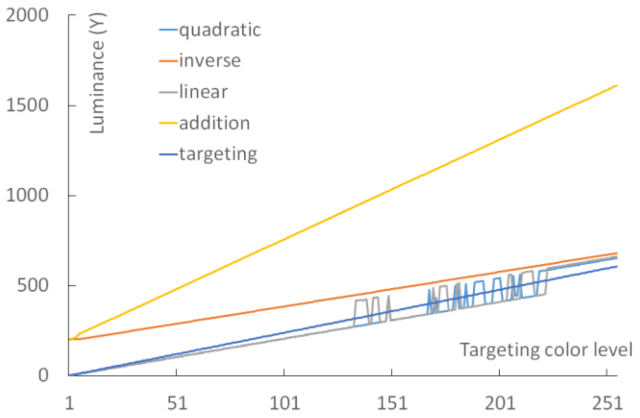

Figure 6. Luminance variation for target red level

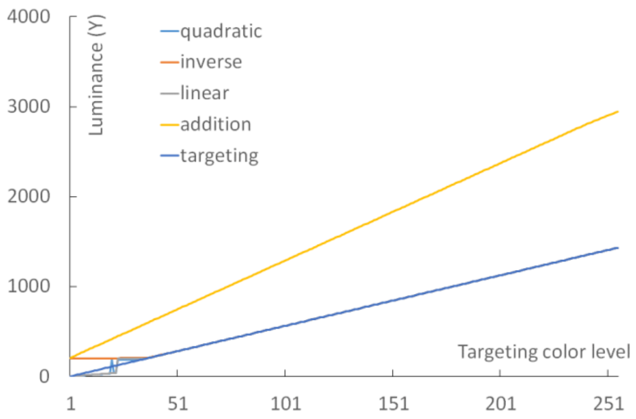

Figure 7. Luminance variation for target cyan level

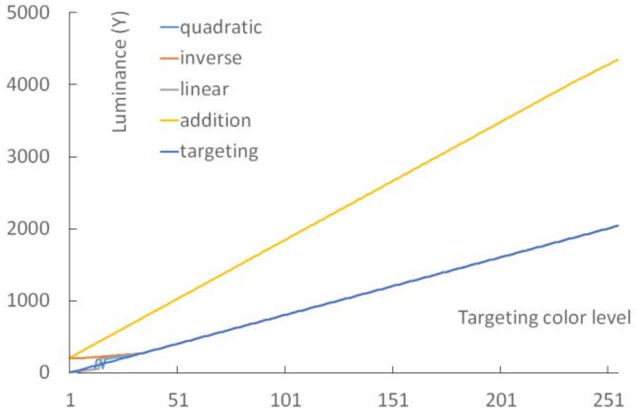

Figure 8. Luminance variation for target white level

The coefficients of the models were calculated in the XYZ color coordinate system by using regression of the measured data. The quadratic form of these coordinates was obtained by performing matrix operation. A cost function was defined for the index to determine the minimum. The SSM uses non-inverse matrix operations and provides accurate tracking of the target color. An experiment was performed using the proposed algorithm in a machine vision system. The result showed that the proposed model generates the target color coordinate better than other methods, except under the low luminance condition.

The proposed methods also determined the input levels to be lower than that of the other methods, thus indicating that it can save the electrical energy required to drive the RGB LEDs.

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