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A New XYZ Color Correction Algorithm Using Random Set of Three Colors: XCCA

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ABSTRACT:XYZ color sensor can be widely applied to bio-medical area such as food engineering and digital dentistry. Four-color matrix algorithm has been used for incorporating the environmental effects in XYZ color values' measurement. However, this conventional algorithm lacks universality because it needs a special color chart that should provide primary colors. Thus, we propose a new correction algorithm, called XCCA; that is based on a random set of three colors rather than the four primary colors. The maximum correction error rate was 6.2% by XCCA compared to 7.7% by commercial color sensor.

KEY WORDS: XYZ color sensor, color correction, XYZ color space, tristimulus value.

I.INTRODUCTION

Color sensor can be used in various biomedical area such as food decay measurement and dentistry. Food decay can be detected by measuring food poisoning bacteria-specific colors. Also, when treating dental implants, the exact measurement of the surrounding teeth can have the better implant results (Peng et al., 2017). In particular, XYZ sensors provide accurate data that is based on a color space that matches that of human visual cells (Fairchild, 2015). As shown in figure 1, an XYZ color sensor measures the colors of objects in line with a specific wavelength and expresses colors with tristimulus values X, Y, and Z.

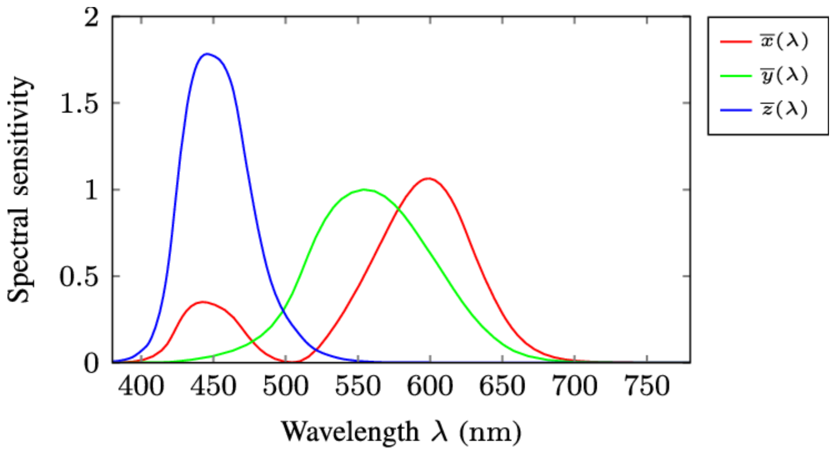

Figure 1. Color matching function of CIE XYZ standard observer (Kerr, 2010)

Each tristimulus value is modeled after the reaction function of human cone cells, and this function is called the International Commission on Illumination (CIE) standard observer. Theoretically, a chromaticity diagram of a color

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space expresses all colors that the human eye can see (Wyszecki and Stiles, 1982). This color space is called a CIE XYZ color space and can be replaced with an RGB color space by linear transformation. The tristimulus values X, Y, and Z, with wavelength λ, are determined as follows (Hunt and Pointer, 1987):

$$X = \int_0^\infty I(\lambda)\,\bar{x}(\lambda)\,d\lambda\,,\ Y = \int_0^\infty I(\lambda)\,\bar{y}(\lambda)\,d\lambda\,,\ Z = \int_0^\infty I(\lambda)\,\bar{z}(\lambda)\,d\lambda\,, \qquad (1)$$

where I(λ) denotes the spectrum output distribution function. The tristimulus values are calculated by the sum of the wavelength intensities in a specific region in the wavelengths of light reflected from an object. Therefore, the tristimulus values measured with an XYZ color sensor differ from the real values because of certain variables, such as illumination, distance from the object, and reflectivity of the light illuminated to the specific region. In other words, measurement of the tristimulus values is greatly affected by the environment.

The rest of this paper is organized as follows. Section 2 describes the characteristics and disadvantages of the existing algorithm. Section 3 explains the proposed algorithm, called XCCA. Section 4 verifies the validity of XCCA, and Section 5 presents the conclusions.

II. RELATED WORKS

Existing standard correction algorithm is the four-color matrix method (Ohno and Hardis, 1997). This algorithm was designed on the basis of the additivity of the tristimulus values of the four primary colors. It uses the fact that the sum of all Xs after normalizing the primary colors is equal to the X value of white. When equations are established for Y and Z as well, a random coefficient that determines the relationship between the X, Y, and Z values of the primary colors can be calculated. With use of this coefficient, the values measured in the configured environment can be corrected to the color space of the standard illuminant.

One disadvantage of this method is that it can be used only when the primary colors can be measured. In other words, a special color chart that provides primary colors is required. However, obtaining a special primary color chart can be challenging when developing an XYZ color sensor platform. For example, even ColorChecker, which is widely utilized as a standard color chart, does not provide a primary value (X-rite, 2019 Brucelindbloom, 2019) . The main reason is that most color charts were developed for image correction in cameras (Hong et al., 2000).

III. PROPOSED ALGORITHM: XCCA

This paper proposes an algorithm that represents original colors by correcting the tristimulus values measured with a color sensor of the CIE XYZ system, which is suitable for a random, non-standard illuminant environment. Basically, the proposed algorithm uses the polynomial form of matrix inversion. Our method is unique in that it uses a random set of three colors instead of the four primary colors (red, green, blue, and white).

First, an industrial color chart and reference values that match this chart are prepared. In general, Munsell, CIE 1931 XYZ, and RGB standard color systems are supported (McCamy et al., 1976). Each color system can be converted into an XYZ color system by linear transformation, and the reference XYZ values can be determined by using the resulting XYZ color system. The proposed algorithm determines the correction coefficients of X, Y, and Z by using three values of random colors in the color chart. Incorrect values can be obtained if same colors exist or the colors used cannot cover the total wavelength region. Therefore, three different colors should be used. Eq. (2) uses the linear relationship between the values measured in the XYZ color sensor platform of random colors A, B, and C and the tristimulus values of the reference A, B, and C values in the actual CIE XYZ color space. Eq. (3) and (4) express Y and Z, respectively, in the same way as does Eq. (2). In Eqs. (2), (3), and (4), the left side consists of the X, Y, and Z values measured in A, B, and C, and the right side consists of the reference X, Y, and Z values of colors A, B, and C.

$$\begin{bmatrix} X_{A_m} & Y_{A_m} & Z_{A_m} \\ X_{B_m} & Y_{B_m} & Z_{B_m} \\ X_{C_m} & Y_{C_m} & Z_{C_m} \end{bmatrix} \begin{bmatrix} a_1 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} X_{A_R} \\ X_{B_R} \\ X_{C_R} \end{bmatrix}, \qquad (2)$$

$$\begin{bmatrix} X_{A_m} & Y_{A_m} & Z_{A_m} \\ X_{B_m} & Y_{B_m} & Z_{B_m} \\ X_{C_m} & Y_{C_m} & Z_{C_m} \end{bmatrix} \begin{bmatrix} a_2 \\ b_2 \\ c_2 \end{bmatrix} = \begin{bmatrix} Y_{A_R} \\ Y_{B_R} \\ Y_{C_R} \end{bmatrix}, \qquad (3)$$

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$$\begin{bmatrix} X_{A_m} & Y_{A_m} & Z_{A_m} \\ X_{B_m} & Y_{B_m} & Z_{B_m} \\ X_{C_m} & Y_{C_m} & Z_{C_m} \end{bmatrix} \begin{bmatrix} a_3 \\ b_3 \\ c_3 \end{bmatrix} = \begin{bmatrix} Z_{A_R} \\ Z_{B_R} \\ Z_{C_R} \end{bmatrix}. \quad (4)$$

Here, the coefficients a, b, and c for transformation can be expressed as follows:

$$\begin{bmatrix} a_1 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} X_{A_m} & Y_{A_m} & Z_{A_m} \\ X_{B_m} & Y_{B_m} & Z_{B_m} \\ X_{C_m} & Y_{C_m} & Z_{C_m} \end{bmatrix}^{-1} \begin{bmatrix} X_{A_R} \\ X_{B_R} \\ X_{C_R} \end{bmatrix}, \quad (5)$$

$$\begin{bmatrix} a_2 \\ b_2 \\ c_2 \end{bmatrix} = \begin{bmatrix} X_{A_m} & Y_{A_m} & Z_{A_m} \\ X_{B_m} & Y_{B_m} & Z_{B_m} \\ X_{C_m} & Y_{C_m} & Z_{C_m} \end{bmatrix}^{-1} \begin{bmatrix} Y_{A_R} \\ Y_{B_R} \\ Y_{C_R} \end{bmatrix}, \quad (6)$$

$$\begin{bmatrix} a_3 \\ b_3 \\ c_3 \end{bmatrix} = \begin{bmatrix} X_{A_m} & Y_{A_m} & Z_{A_m} \\ X_{B_m} & Y_{B_m} & Z_{B_m} \\ X_{C_m} & Y_{C_m} & Z_{C_m} \end{bmatrix}^{-1} \begin{bmatrix} Z_{A_R} \\ Z_{B_R} \\ Z_{C_R} \end{bmatrix}. \quad (7)$$

Furthermore, we define the correction matrix $\mathbb{R}$ as follows:

$$\mathbb{R} = \begin{bmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{bmatrix}. \quad (8)$$

If the color data measured in the same environment comprises $X_m,\ Y_m,\ and Z_m$, then the XYZ value M' corrected by the standard illuminant D65 color space using the correction matrix $\mathbb{R}$ can be determined by using the following equation:

$$\mathrm{M}' = \mathbb{R} \begin{bmatrix} X_m \\ Y_m \\ Z_m \end{bmatrix}. \quad (9)$$

Then, the original color can be displayed after transforming M' into RGB.

IV. EXPERIMENTS

In this section, the operation of the proposed color correction algorithm was tested and verified by setting up an actual platform. For the industrial color chart used in the correction algorithm, the Korean Standards (KS) color C&D 155 of Korea Color Design Institute (KCDI) was employed (KS Standard Color, 2019). This color chart was produced in accordance with Korean industrial standards and support reference colors represented by the Munsell color system. In this experiment, 131/R, 135/G, and 137/B were utilized as the three random colors A, B, and C of the color chart. These colors had the reference values of 7.5R 4/14, 2.5G 4/10, and 2.5PB 4/10, respectively, in the Munsell color system. Each color was converted to sRGB through a Munsell-to-RGB conversion table, and then, the reference X, Y, and Z values were determined by RGB-to-XYZ conversion (Munsell, 2019). This process is outlined in table 1.

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Table 1. Reference color values of three random colors for our experiment in each color system

KS C&D 155 Color Chart	**Munsell Color System**	**sRGB Color System**			**XYZ Color System**		
		R	G	B	X	Y	Z
131/R	7.5R 4/14	188	32	36	21.1	11.6	2.8
135/G	2.5G 4/10	0	115	60	6.9	12.6	6.3
137/B	2.5PB 4/10	0	100	169	11.7	12.0	39.2

For the new algorithm's verification, a platform was set up using XYZ color sensors to keep the measurement environment constant, as shown in figure 2.

Figure 2. Platform setup

The XYZ color sensor used in the platform was an ams AS7261 (AS7261, 2019), which conforms to the CIE 1931 2° standard observer. A white LED was attached to detect the illumination at every wavelength. During the measurement, the illumination was kept constant by activating the LED with all the lights blocked. Furthermore, the distance to the measured object was fixed to 1 cm through the case design to maintain a constant distance from the sensor. Then, the three experimental colors in the KS C&D 155 color chart were measured. Table 2 outlines the measurement results.

Table 2. X, Y, and Z values of three random colors measured in the experimental environment

KS C&D 155 Color Chart	**Measured XYZ Value**		
	X	Y	Z
131/R	75.3	62.8	25.2
135/G	18.5	22.9	23.5
137/B	67.4	71.5	120.0

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With use of Eq. (5), table 1, and table 2, the equation for the coefficients for correction of the X value, a_1, b_1, and c_1, can be expressed as follows:

$$\begin{bmatrix} a_1 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} 75.3 & 62.8 & 25.2 \\ 18.5 & 22.9 & 23.5 \\ 67.4 & 71.5 & 120.0 \end{bmatrix}^{-1} \begin{bmatrix} 21.1 \\ 6.9 \\ 11.7 \end{bmatrix} = \begin{bmatrix} -0.32 \\ -1.56 \\ -0.20 \end{bmatrix}. \quad (10)$$

Similarly, with use of tables and Eqs. (6) and (7), a_2, b_2, and c_2 and a_3, b_3, and c_3 can be expressed as follows:

$$\begin{bmatrix} a_2 \\ b_2 \\ c_2 \end{bmatrix} = \begin{bmatrix} 75.3 & 62.8 & 25.2 \\ 18.5 & 22.9 & 23.5 \\ 67.4 & 71.5 & 120.0 \end{bmatrix}^{-1} \begin{bmatrix} 11.6 \\ 12.6 \\ 12.0 \end{bmatrix} = \begin{bmatrix} 0.81 \\ 2.20 \\ 0.21 \end{bmatrix}, \quad (11)$$

$$\begin{bmatrix} a_3 \\ b_3 \\ c_3 \end{bmatrix} = \begin{bmatrix} 75.3 & 62.8 & 25.2 \\ 18.5 & 22.9 & 23.5 \\ 67.4 & 71.5 & 120.0 \end{bmatrix}^{-1} \begin{bmatrix} 2.8 \\ 6.3 \\ 39.2 \end{bmatrix} = \begin{bmatrix} -0.20 \\ -0.33 \\ 0.29 \end{bmatrix}. \quad (12)$$

With use of Eqs. (8), (10), (11), and (12), the correction matrix $\mathbb{R}$ can be obtained as follows:

$$\mathbb{R} = \begin{bmatrix} -0.32 & 0.81 & -0.20 \\ -1.56 & 2.20 & -0.33 \\ -0.20 & 0.21 & 0.29 \end{bmatrix}. \quad (13)$$

When $\mathbb{R}$ is multiplied to the measured X, Y, and Z values of random colors, the environmental variables are corrected, and the values are matched to the standard illuminant D65 color space of the CIE XYZ color system. In other words, they are converted to values for which the XYZ-to-RGB conversion can be used. For the conversion to the RGB color space, the basic equation for XYZ D65-to-RGB conversion is used as follows (Pharr and Humphreys, 2010):

$$\begin{bmatrix} 3.240479 & 1.53715 & -0.498535 \\ -0.969256 & 1.875991 & 0.041556 \\ 0.055648 & -0.204243 & 1.057311 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \quad (14)$$

Finally, 14 colors were measured and corrected through the application of XCCA. Then, the results were compared with the reference colors in the color chart converted to RGB values. Table 3 outlines the comparison results.

Table 3. Comparison between reference colors and the RGB values of the colors corrected

by XCCA using colors red, green, and blue

Color	**Reference Color**			**XCCA Application Results**			**Delta E**
	R	G	B	R_{XCCA}	G_{XCCA}	B_{XCCA}	
Red	178	46	61	178	46	61	0
Orange	238	111	21	252	98	25	7.54
Yellow	235	197	63	247	189	51	6.84
Yellow Green	135	189	77	130	180	63	1.97
Green	0	115	60	0	115	60	0
Blue Green	0	84	106	0	96	108	6.46

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Blue	0	100	169	0	100	169	0
Navy Blue	0	97	183	13	107	171	12.39
Purple	103	47	127	100	71	119	10.08
Reddish Purple	135	25	81	126	50	74	6.04
Pink	238	148	168	234	146	159	2.96
Brown	147	79	31	158	79	51	8.19
White	244	239	246	244	245	238	8.37
Gray	125	121	127	128	125	130	1.65

For calculation of the error rate e, the error of the squares of R_{XCCA}, G_{XCCA}, and B_{XCCA} corrected from the reference R, G, and B values by XCCA was divided by the sum of the squares of all possible cases, and the result was represented as a percentage. The equation for the error rate is expressed as follows:

$$e = 100\sqrt{\frac{(R-R_{XCCA})^2+(G-G_{XCCA})^2+(B-B_{XCCA})^2}{255^2+255^2+255^2}} \quad . \tag{15}$$

Similar experiment results were made using a commercial color sensor and the XCCA as shown in table 4 (Nix 2019).

Table 4. Comparison between the reference colors and the RGB values of a commercial color sensor

Color	**Reference Color**			**Commercial Color Sensor Value**			**Delta E**
	R	G	B	R_c	G_c	B_c	
Red	178	46	61	173	53	64	1.39
Orange	238	111	21	235	108	40	4.14
Yellow	235	197	63	230	193	62	1.00
Yellow Green	135	189	77	134	181	70	2.15
Green	0	115	60	0	121	69	2.17
Blue Green	0	84	106	0	97	113	6.39
Blue	0	100	169	0	106	162	9.05
Navy Blue	0	97	183	9	106	168	15.35
Purple	103	47	127	94	79	120	13.37

Reddish Purple	135	25	81	123	53	73	12.57
Pink	238	148	168	237	150	162	1.35
Brown	147	79	31	141	86	53	3.03
White	244	239	246	244	242	235	7.55
Gray	125	121	127	122	128	128	7.50

The maximum error rates were 6.2% for the correction by XCCA and 7.7% for the correction by the commercial color sensor. Most errors were caused not by the algorithm but by the measurement environment, the wavelength sensitivity of the sensor, and similar factors.

V. CONCLUSION

This paper proposes an algorithm called XCCA, which performs color correction for XYZ color sensors using a random set of three colors. XCCA determines the correction matrix $\mathbb{R}$ by using the linear relationship of Eqs. (2)–(4) and corrects the newly measured X, Y, and Z values by using $\mathbb{R}$. As shown in figure 2, an actual platform for XCCA was produced with this platforming. The values measured in a non-standard illuminant environment were corrected. In order to verify the XCCA, similar experiment was made using commercial color sensor. The maximum error rate was 6.2% for the correction by XCCA compared to 7.7% for the correction by the commercial color sensor.

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