Color characteristic design for color scanners

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We propose a method of quantitative color characteristic design for color scanners. We used colorimetric simulation with an optical model and a color conversion circuit to match the scanner color characteristic to an objective color standard. A compensation matrix is defined using the least-squares method to minimize the average error for many colors. To determine the matrix, a color space must be selected. We compared the results of conversion using matrices obtained in the CIELAB color space and in the RGB color space. The comparison shows that both conversions are nearly the same. Using computer simulation, we designed a color scanner with excellent conversion performance. The average color difference for 440 colors was ~1.3.
Key words: Color scanner, color conversion, color space, least-squares method.

I. Introduction

Recent developments in the computer field have made full-color image processing practical and easy. Digital color imaging is becoming common and several color scanners have been developed.[1–4] The most important requirement for color scanners is precise color digitization. For this, color must be expressed quantitatively. The CIE-RGB standard (human eye characteristic) established by the CIE (Commission Internationale de l'Eclairage) and the NTSC-RGB TV standard are in common use. If the scanner output follows a common standard, image processing and display is more precise. However, a scanner output standard is yet undefined, although with the growth of image processing this will become a necessity.

For the scanner's output to match a standard, its spectral response must also match a standard. We developed a technique with which the scanner's color characteristic can be determined using computer colorimetric simulation. This paper describes the design of color scanner characteristics and a design example.

II. Color Scanner Design

A. Scanner Structure

Figure 1 is a schematic of the color scanner. A color document is illuminated by a white fluorescent lamp, and the reflected light is focused by a lens through the color filters and onto the CCD sensor. The sensor translates the incident light to an electrical signal. The sensor output is digitized by the A–D converter and the color conversion circuit converts the digital signal into red, green, and blue signals. However, since the sensor's output does not match an objective standard, compensation is required.

B. Design

1. *Objective Standard*

For precise color digitization, we must first decide on an objective standard. The standard used depends on the application. For example, when an image is displayed on a CRT, the NTSC-RGB standard is used. For color printing, the YMC (yellow, magenta, cyan) is used. In general, the XYZ or RGB (NTSC-RGB or CIE-RGB) systems are used.

2. *Optical Elements*

The light source, lens, color separation filters, and CCD sensor must be selected to match the standard. However, there are bright lines in the fluorescent lamp's spectrum and the CCD's response is uneven. Furthermore, some standards (such as the NTSC-RGB) have a negative response (see Fig. 2), while the optical elements of the scanner have positive responses. Electronic compensation of sensor output is necessary to create a negative response. We selected optical elements so that only the positive response matches the standard.

3. *Electronic Compensation*

Conversion performance in the CIELAB color space without negative response decreases the colorfulness

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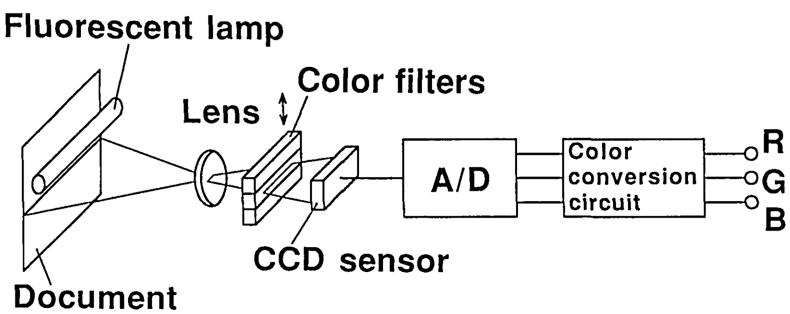

Fig. 1. Model of the color scanner.

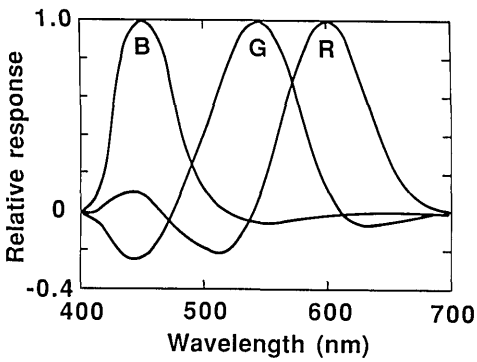

Fig. 2. NTSC-RGB response.

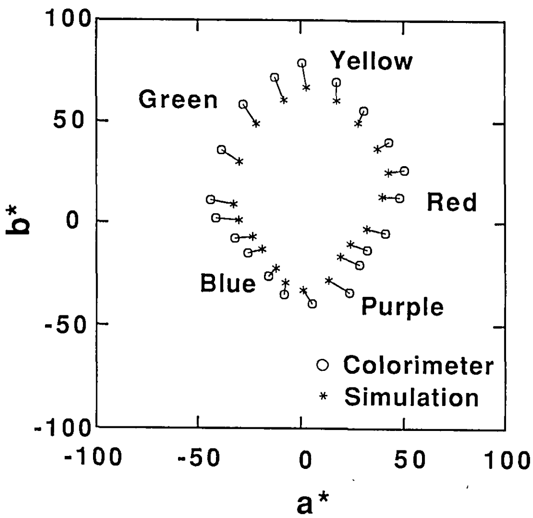

Fig. 3. Conversion performance without negative response.

of the digitized colors (see Fig. 3). For precise color digitization, a negative response must be created electronically. This is achieved with matrix compensation. Matrix compensation can be nonlinear or linear with two degrees of conversion. In our study, we examine a simple method of conversion which makes hardware implementation comparatively easy. We used computer simulation to determine the matrix.

4. *Performance Evaluation*

To evaluate color scanner performance, the characteristic response of the eye must be considered. The eye evaluates color error by combination of hue, brightness, and colorfulness. If scanner performance is evaluated using a color system which matches visual characteristics, the perceived error will be minimized. We evaluated the scanner performance in the CIELAB color space (see Fig. 4). This space was determined by CIE and is based on the eye's color response; L^* represents brightness and the a^* and b^* values define hue and colorfulness. The distance between colors is the color difference and is proportional to the eye's sensitivity. The difference between two colors can be explained quantitatively using the color difference. We believe that the error should be evaluated using this color difference.

The performance of the color scanner is most affected by the method of electronic compensation used.

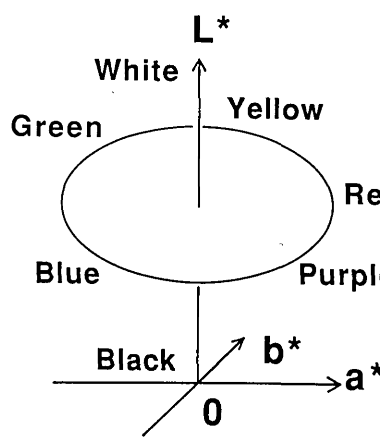

Fig. 4. CIELAB color space.

III. Design of the Compensation Matrix

A. Model of the Color Scanner

The matrix which minimizes average error for many colors is designed using computer colorimetric simulation of a color scanner model. Computer-aided design shortens the evaluation time.

Sensor output Oi is expressed by

$$Oi = \int D(\lambda)L(\lambda)Fi(\lambda)C(\lambda)S(\lambda)d\lambda, \tag{1}$$

where i = separation color (1,2,3);
λ = wavelength;
Oi = sensor output;
$D(\lambda)$ = spectral reflectance from the color specimen;

$L(\lambda)$ = spectrum of the fluorescent lamp;
$Fi(\lambda)$ = spectral transmittance of the color filter;
$C(\lambda)$ = spectral sensitivity of the CCD sensor; and
$S(\lambda)$ = spectral response of other optical elements.

The matrix operation is explained by Eq. (2):

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} m_1 & m_2 & m_3 \\ m_4 & m_5 & m_6 \\ m_7 & m_8 & m_9 \end{pmatrix} \begin{pmatrix} O_1 \\ O_2 \\ O_3 \end{pmatrix}, \tag{2}$$

where $\mathbf{T}(R,G,B)$ = scanner output;
$\mathbf{M}(m_1\text{–}m_9)$ = conversion matrix; and
$\mathbf{O}(O_1,O_2,O_3)$ = sensor output.

B. Definition of Matrix Elements

To compensate using Eq. (2), the nine elements of the matrix must be determined. These elements depend on the optics and an objective standard response. Generally, the nine elements can be determined from nine equations obtained from the three colors (three sets of R,G,B values). If these elements are determined from three colors, these three colors can be converted perfectly, but there is no guarantee that other colors will be digitized precisely. For precise digitization of all colors, the scanner's spectral response must match a standard. However, because of the bright lines in the fluorescent lamp's spectrum, the CCD's uneven spectral response, and the negative response of the standards, it is impossible to match the synthesized scanner spectral response and the standard response perfectly. To get as close a match as possible, a matrix which minimizes the average error for many colors must be determined. For this, the least-squares method is generally used. Matrix elements are defined to minimize the average error between color values in the standard and sensor output.

The method of minimizing average error in the RGB color space is expressed in Eq. (3)[5]:

$$\mathbf{M} = (\mathbf{P}n\mathbf{O}n^t)(\mathbf{O}n\mathbf{O}n^t)^{-1}, \tag{3}$$

where $\mathbf{P}n$ = color value in the objective standard for n color samples,
$\mathbf{O}n$ = sensor output for n color samples, and
$\mathbf{M}$ = conversion matrix.

Terms $\mathbf{P}n$ and $\mathbf{O}n$ are three-row, n-column matrices; $\mathbf{O}n$ is calculated from Eq. (1) using a computer and $\mathbf{P}n$ is the color value consisting of n color samples in a standard, where n is more than three and is a fairly large number. These values were measured with a colorimeter. From Eq. (3) conversion matrix $\mathbf{M}$ is fixed to minimize the errors of $\mathbf{P}n$ and $\mathbf{O}n$.

C. Problem for Matrix Definition

There are two problems with determining matrix elements by the least-squares method:

1. *Selection of Color Space*

Until now, matrix elements were determined in the RGB color space used for scanner output. The matrix elements are defined so that the average error between the measured and the simulated RGB values is minimized. However, to decrease the perceptible color difference, the matrix must be determined in a color space which matches the eye's sensitivity.

2. *Selection of Color Specimens*

When the matrix is calculated using Eq. (3), n color samples must be selected. Compensation is influenced considerably by this selection. Therefore, the second problem is how to select these samples.

D. Color Space and Color Selection

We selected colors equally distributed in the CIELAB color space and defined the conversion matrix so that the average color difference between the measured and simulated values is minimized. (We call this the LAB matrix.) Equally distributed means that the distance between colors in the CIELAB color space is equal. If the color distribution is equally weighted, the conversion performance for many colors should be excellent. To compare the conversion performance with the LAB matrix, a matrix using RGB values was defined. (We call this the RGB matrix.)

In Sec. IV we compare conversion performance of the two matrices.

IV. Results of Matrix Design

A. Design Condition

To calculate the sensor output, Eq. (1), optical elements must be selected and their spectral responses measured. We used a white fluorescent lamp which contains all the colors in the spectrum, glass RGB filters, a CCD linear image sensor, ultraviolet and heat absorbing filters, a lens, and a mirror. The spectral responses of the fluorescent lamp, color separation filters, CCD sensor, and ultraviolet and heat absorbing filters are shown in Figs. 5–8. The responses of lens and mirror are almost even over the visible spectrum.

Spectrum reflectances from color samples which were used in the simulation were measured. We measured 1142 color chips of the Japanese Industrial Standard. This standard contains 40 hues, 9 brightness levels, and 14 colorfulness levels; the L^*, a^*, and b^* values were calculated from the measured RGB values and are stored in computer memory. For example, colors with an L^* value of 60 are shown in Fig. 9. Using these data, the scanner output was calculated using Eq. (1).

B. Design Calculations

We selected colors from the 1142 measured colors in the CIELAB color space having distances of 10, 20, or 30. Six selected color groups are shown in Table I. For example, Fig. 10 shows the selected colors (group 10) at a distance of 10 on the a^*b^* plane for which L^* is 60. The colors in Fig. 9 are concentrated at the center, but the colors in Fig. 10 are equally distributed.

Six LAB matrices and six RGB matrices were defined by the least-squares method using colors from Table I. Conversion performances of these matrices were examined. We used the Marquardt least-

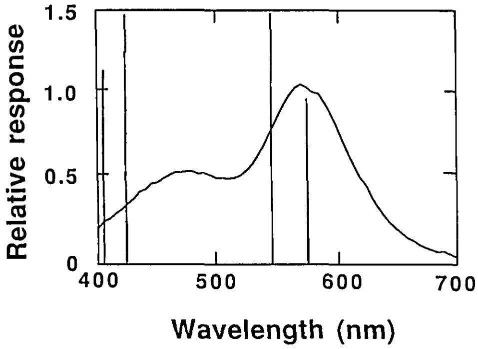

Fig. 5. Fluorescent lamp spectrum.

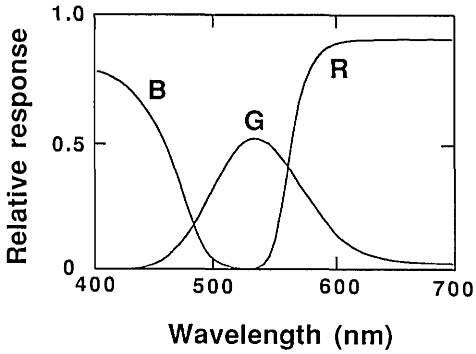

Fig. 6. RGB filter transmittance.

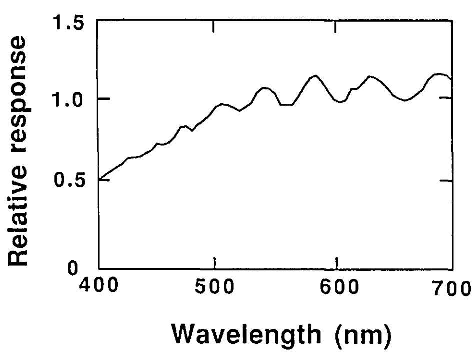

Fig. 7. CCD sensor sensitivity.

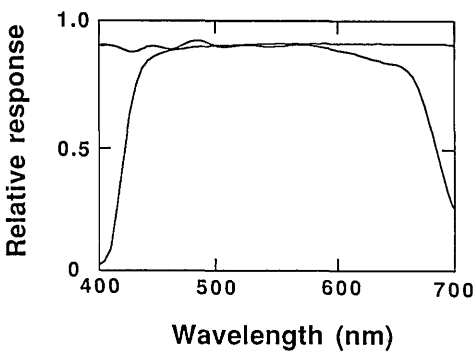

Fig. 8. Ultraviolet and heat absorbing filter transmittance.

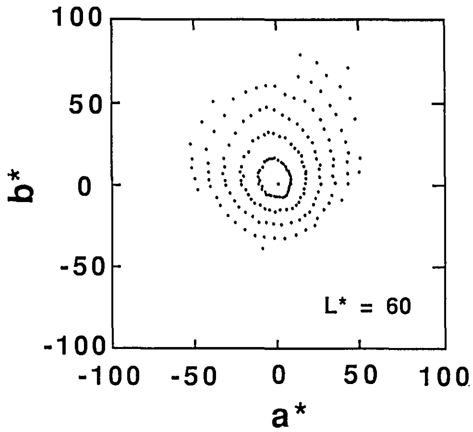

Fig. 9. JIS color chips.

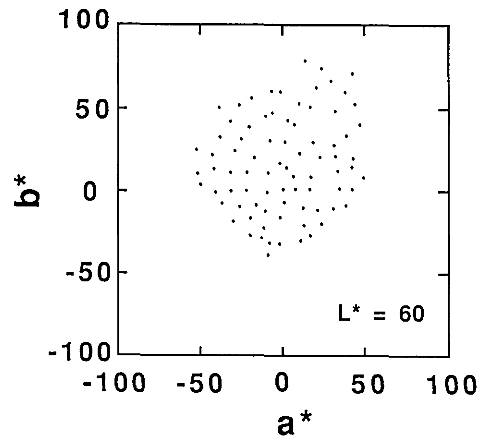

Fig. 10. Selected colors.

Table I. Color Selection

Color group	Distance	L*	Number
10	10	10 - 90	440
20-1	20	10, 30, 50, 70, 90	52
20-2	20	20, 40, 60, 80	57
30-1	30	10, 40, 70	19
30-2	30	20, 50, 80	18
30-3	30	30, 60, 90	17

squares method for the LAB matrices.[6] This is a nonlinear problem and cannot be solved analytically. Because of the nonlinear problem, there are many local solutions decided by an initial condition (matrix elements). In our estimation, we used the elements which are obtained from the least-squares method in the RGB color space.

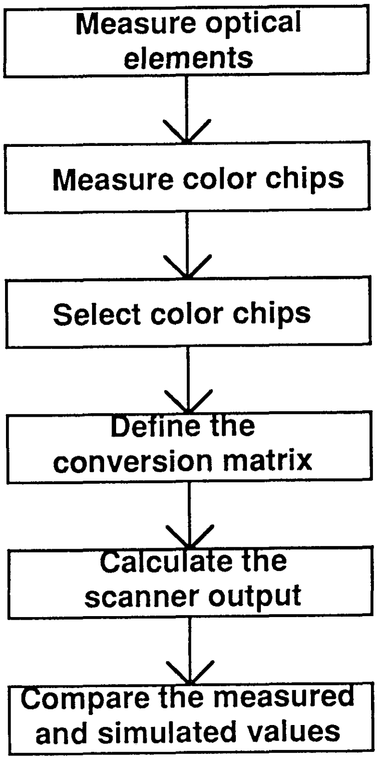

Fig. 11. Calculation process.

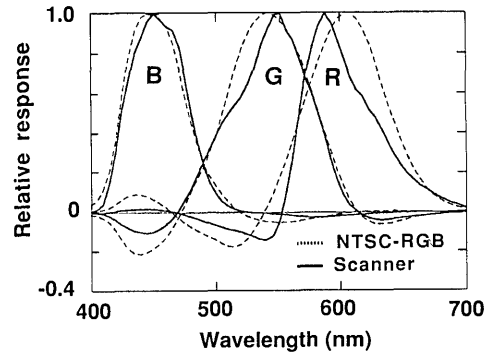

Fig. 13. Synthesized spectral response.

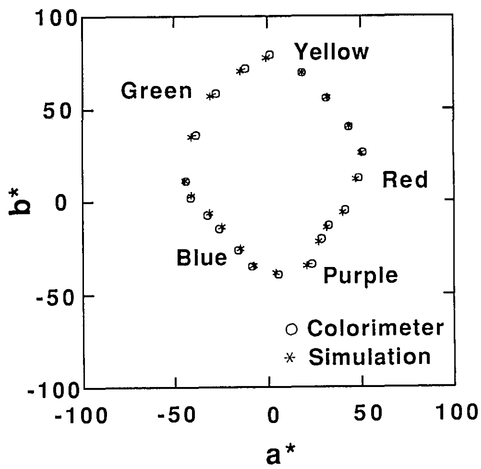

Fig. 14. Conversion performance for twenty colors.

Conversion performances were evaluated for 440 colors, using the average color difference between measured and simulated values. For reference, maximum color differences were calculated. The objective standard was NTSC-RGB. The process of evaluation is shown in Fig. 11.

C. Results

Figure 12 shows the conversion performances of the LAB and RGB matrices. The average errors using the LAB matrices and the RGB matrices are <1.3, almost the same. The difference between the LAB and RGB average conversion performance is very small. However, the maximum errors using the LAB matrices are about 5. This is half of the RGB matrices.

Figures 13 and 14 show the scanner color performance with the LAB matrix using the group 10 colors.

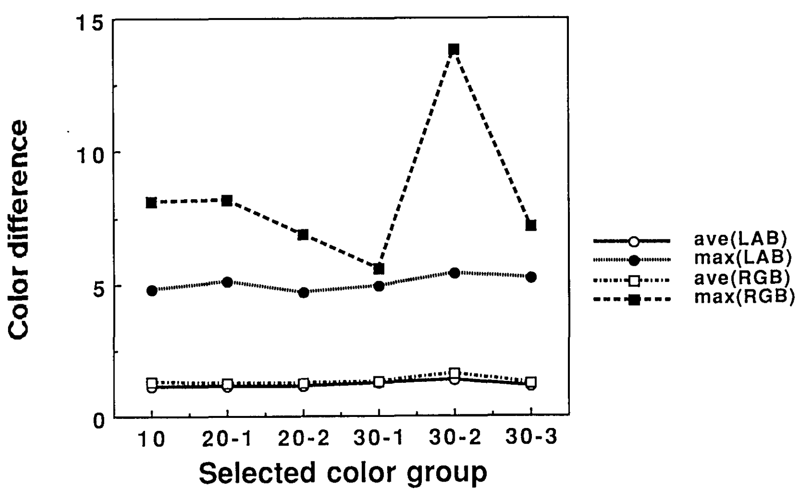

Fig. 12. LAB and RGB matrices conversion performances.

Figure 13 is the synthesized spectral response which combines the optical system with the conversion matrix. Scanner characteristics almost agree with the NTSC-RGB standard. Figure 14 is the simulated conversion performance of the scanner with the characteristics shown in Fig. 13. Twenty colors were precisely digitized.

If the colors for the definition of the matrix are equally selected in the CIELAB color space, precise color digitization can be achieved. Both performances, with the LAB and the RGB matrices, are almost the same.

V. Conclusion

We examined a method of precise color digitization for color scanner design. The scanner spectral response matches an objective standard. The compensation matrix is defined to minimize the average error for many colors equally distributed in the CIELAB color space. This space matches the eye's sensitivity to color. The average errors using two types of matrix, one obtained from the RGB color space and the other from the LAB color space, are nearly the same and are very small.

We designed a color scanner based on computer simulation and confirmed excellent conversion performance. The average color difference for 440 colors was ~1.3.

Appendix

(1) NTSC-RGB and XYZ relation:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.607 & 0.174 & 0.201 \\ 0.299 & 0.587 & 0.114 \\ 0 & 0.066 & 1.117 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}. \tag{A1}$$

(2) XYZ and CIELAB relation:

$$L^* = 116(Y/Yn)^{1/3} - 16, \tag{A2}$$

$$a^* = 500[(X/Xn)^{1/3} - (Y/Yn)^{1/3}], \tag{A3}$$

$$b^* = 200[(Y/Yn)^{1/3} - (Z/Zn)^{1/3}]. \tag{A4}$$

(3) Color difference (E^*):

$$E^* = \sqrt{(L^*1 - L^*2)^2 + (a^*1 - a^*2)^2 + (b^*1 - b^*2)^2}, \tag{A5}$$

where R,G,B = values in the RGB color space;
X,Y,Z = tristimulus values;
Xn,Yn,Zn = tristimulus values of a perfect reflecting diffuser; and
L^*,a^*,b^* = values in the CIELAB color space.

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