Spectral Color Management - Color Scanner -

Nobuaki Usui and Jun-ichi Odagiri*
I/O Systems Lab., Fujitsu Laboratories Ltd.
Atsugi-shi, Kanagawa-ken, Japan

Abstract

Color management with look-up tables now is becoming widely used and the ICC profile format adopts it. While it is a realistic solution in case that the specifications of scanners and printers have already been fixed, it is unrealistic to apply it to the development of scanners and printers. It is because colors and color values are not presumed until a controller and engine have been completed. It means that specifications must be changed on a trial and error basis to get the desired colors and much more time and money is spent by using look-up tables.

A new interpolation method has been developed to reduce time and monetary cost by designing a controller and engine, and predicting colors done in parallel. For printers, Print Simulator was made public at PICS2000 in March 2000. In this paper, we propose a method to manage colors on a spectral basis for color scanners. The method seems to be practical because it requires less time and cost less while providing good accuracy. An outline of this method is written below:

(1) Specific color patches are selected by the singular value decomposition method.
(2) Spectral characteristics of a scanner are calculated with the color patches.
(3) Based on the spectral characteristics on Red (R), Green (G) and Blue (B), the relationship between colorimetric values and RGB values input from a scanner is defined.

Introduction

The previous method, which uses look-up tables composed of 288 color patches measured, for color management is very useful to apply it to the scanners of which specifications have already fixed. But for the developers of scanners, the colors output by a scanner are presumed only after it is manufactured because it is necessary to input 288 color patches and therefore the sequential process of manufacturing steps is inevitable.

A new method suitable both for color management and designing scanners is proposed here as shown in Figure 2.

The method has the following advantages:

(1) To begin with, the spectral characteristics of R,G,B are calculated based on less color patches in this method. Therefore, the characteristics of R,G,B can be adjusted to get a desired scanner and changes of R,G,B are carried out not on a trial and error basis, only on the computer.

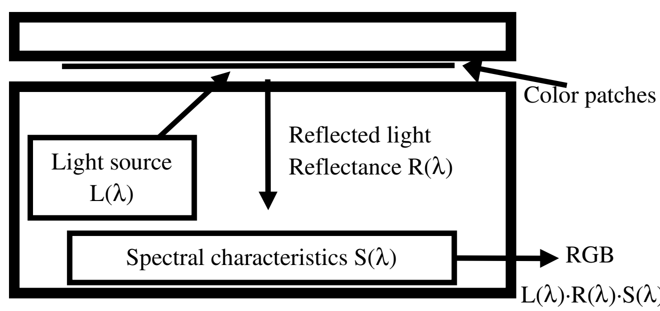
As a result of that, manufacturing a scanner and predicting colors are separated and done in parallel.

(2) Such presumption can be done by using less color patches. This means less influence on perturbation of estimated accuracy.

In this paper, I will explain the algorithm to presume the spectral characteristics of R,G,B and how to make a color profile by using these characteristics.

Mathematical Model of Scanners

The schematic diagram for scanners is shown in Figure 1.



(1) Color patches are illuminated by the light L(λ).
(2) Light reflected from the patches is measured.
(3) Measured values are converted to the RGB values.

The algorithm is represented as a set of Equations (1), which follows the notes written below:

λ (380,...,730 nm)	: Wavelength
R,G,B	: Values of (R,G,B)
R(λ) (λ=380,...,730)	: Reflectance data
L(λ) (λ=380,...,730)	: Spectral characteristics of light source
S(λ) (λ=380,...,730)	: Spectral characteristics of R,G,B

$$R = \sum_{\lambda=380}^{730} L(\lambda)\cdot R(\lambda)\cdot S_R(\lambda)$$
$$G = \sum_{\lambda=380}^{730} L(\lambda)\cdot R(\lambda)\cdot S_G(\lambda) \qquad (1)$$
$$B = \sum_{\lambda=380}^{730} L(\lambda)\cdot R(\lambda)\cdot S_B(\lambda)$$

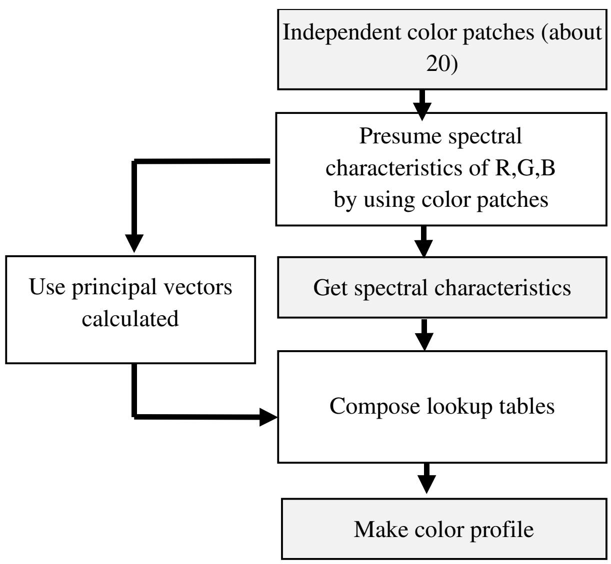


Figure 2. New method for interpolation and making look-up tables

New Method For Presuming Characteristics And Making Look-Up Tables In Color

The method mentioned here is summarized below and shown in Figure 2.

(1) The spectral characteristics of R,G,B are calculated from the measured data of the specific color patches.
(2) Arbitrary color values are interpolated by using the characteristics above and the set of Equation (1).
(3) The look-up tables are composed based on the colors interpolated in (2).

How to Calculate Characteristics of R,G,B

All of the spectral characteristics shall be calculated at every 10nm. A set of simultaneous equations (2) is composed according to Figure 1 and Equation (1) based on the following notes:

Ri,Gi,Bi (*i*=1,...,*N*)	: Values of N set of (R,G,B) to be input
R(i,j) (I=1,...,N) (j= 380,...,730)	: Reflectance data of N colors to be input
LS(i,j) (i=R,G,B) (j=380,...,730)	: Spectral characteristics of R,G,B to be presumed

In the case of the color patches used being less than 36, the following equation (3) shall be used.

$$\begin{pmatrix} R_1 & G_1 & B_1 \\ R_2 & G_2 & B_2 \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ R_N & G_N & B_N \end{pmatrix} = \begin{pmatrix} R_{(1,380)} & R_{(1,390)} & \cdots & \cdots & R_{(1,730)} \\ R_{(2,380)} & R_{(2,390)} & \cdots & \cdots & R_{(2,730)} \\ \vdots & \vdots & \ddots & & \vdots \\ \vdots & \vdots & & \ddots & \vdots \\ R_{(N,380)} & R_{(N,390)} & \cdots & \cdots & R_{(N,730)} \end{pmatrix} \begin{pmatrix} LS_{(R,380)} & LS_{(G,380)} & LS_{(B,380)} \\ LS_{(R,390)} & LS_{(G,390)} & LS_{(B,390)} \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ LS_{(R,730)} & LS_{(G,730)} & LS_{(B,730)} \end{pmatrix} \qquad (2)$$

$$\begin{pmatrix} R_1 & G_1 & B_1 \\ \vdots & \vdots & \vdots \\ R_N & G_N & B_N \\ 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} R_{(1,380)} & R_{(1,390)} & \cdots & \cdots & R_{(1,730)} \\ \vdots & \vdots & & & \vdots \\ R_{(N,380)} & R_{(N,390)} & \cdots & \cdots & R_{(N,730)} \\ 0 & 0 & \cdots & \cdots & 0 \\ \vdots & \vdots & & & \\ 0 & 0 & \cdots & \cdots & 0 \end{pmatrix} \begin{pmatrix} LS_{(R,380)} & LS_{(G,380)} & LS_{(B,380)} \\ LS_{(R,390)} & LS_{(G,390)} & LS_{(B,390)} \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ LS_{(R,730)} & LS_{(G,730)} & LS_{(B,730)} \end{pmatrix} \quad (3)$$

Equations (2) or (3) can be solved by the singular value decomposition (SVD) to presume the values of *LS(i,j)* though numbers of columns and rows of the matrix *R(i,j)* are not the same.

Here, the matrix *R(i,j)* is transformed according to Equation (4). Larger singular values mean more dominant singular vectors corresponding to them and numerical errors which lead to erroneous results can be drastically reduced by ignoring the smaller singular values below a specified accuracy of calculation. In this paper, it is carried out by replacing such values to be ignored by zero.

After SVD is done for Equation (4), Equation (5) is obtained. In Equation (5), *U,V* are the orthogonal matrices. Therefore, *LS(i,j)* is represented as Equation (6). In the matrix of which diagonal components are singular values, each singular value W_i is replaced by its reciprocal $1/W_i$ and zeros are left.

$$\begin{pmatrix} R(1,380) & R(1,390) & \cdots & \cdots & R(1,730) \\ R(2,380) & R(2,390) & \cdots & \cdots & R(2,730) \\ \vdots & \vdots & \ddots & & \vdots \\ \vdots & \vdots & & \ddots & \vdots \\ R(n,380) & R(n,390) & \cdots & \cdots & R(n,730) \end{pmatrix} = \begin{pmatrix} \\ & U & \\ \\ \end{pmatrix} \cdot \begin{pmatrix} W_1 & & & \\ & W_2 & & \mathbf{0} \\ & & \ddots & \\ \mathbf{0} & & \ddots & \\ & & & W_{36} \end{pmatrix} \cdot \begin{pmatrix} P(1,380) & P(1,390) & \cdots & \cdots & P(1,730) \\ P(2,380) & P(2,390) & & & P(2,730) \\ \vdots & \vdots & & & \vdots \\ \vdots & \vdots & & & \vdots \\ P(36,380) & P(36,390) & \cdots & \cdots & P(36,730) \end{pmatrix} \quad (4)$$

Notes:

Wi (*i*=1,...,36)	: Singular values
P (i,j) (*i*=1,...,36) (*j*= 380,...,730)	: Right singular vectors according to each singular values
U(i,j) (*i*=1,...,36) (j=380,...,730)	: Left singular vectors
$X_i, Y_i, Z_i (i = 380,...730)$	: Color matching function (380 – 730 nm)

$$\begin{pmatrix} R_1 & G_1 & B_1 \\ R_2 & G_2 & B_2 \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ R_N & G_N & B_N \end{pmatrix} = \begin{pmatrix} \\ & U & \\ \\ \end{pmatrix} \cdot \begin{pmatrix} W_1 & & & \\ & W_2 & & 0 \\ & & \ddots & \\ 0 & & \ddots & \\ & & & 0 \end{pmatrix} \cdot \begin{pmatrix} \\ & V & \\ \\ \end{pmatrix} \cdot \begin{pmatrix} LSR380 & LSG380 & LSB380 \\ LSR390 & LSG390 & LSB390 \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ LSR730 & LSG730 & LSB730 \end{pmatrix} \quad (5)$$

By using Equation (6), the spectral characteristics of R,G,B are obtained.

How To Make Color Profile

The relationship between R,G,B values and CIEXYZ (1931) is obtained with *LS*(*i,j*) presumed above according to ISO 13655. Equation (7) represents the relationship between the reflectances to be measured and RGB values to be output. Equation (8) means how to convert the reflectances above into values based on CIEXYZ (1931). Therefore, Equation (9) can be derived from Equations (7), (8) and as a result of such derivation, the matrix ***T*** is represented as Equation (10).

$$\begin{pmatrix} LS_{R380} & LS_{G380} & LS_{B380} \\ LS_{R390} & LS_{G390} & LS_{B390} \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ LS_{R730} & LS_{G730} & LS_{B730} \end{pmatrix} = \begin{pmatrix} & & \\ & V^T & \\ & & \end{pmatrix} \cdot \begin{pmatrix} 1/W_1 & & & \\ & 1/W_2 & & 0 \\ & & \ddots & \\ 0 & & & \ddots \\ & & & & 0 \end{pmatrix} \cdot \begin{pmatrix} & & \\ & U^T & \\ & & \end{pmatrix} \cdot \begin{pmatrix} R_1 & G_1 & B_1 \\ R_2 & G_2 & B_2 \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ R_N & G_N & B_N \end{pmatrix} \quad (6)$$

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} LS_{(R,380)} & LS_{(R,390)} & \cdots & \cdots & LS_{(R,730)} \\ LS_{(G,380)} & LS_{(G,390)} & \cdots & \cdots & LS_{(G,730)} \\ LS_{(B,380)} & LS_{(B,390)} & \cdots & \cdots & LS_{(B,730)} \end{pmatrix} \cdot \begin{pmatrix} R_{(i,380)} & R_{(i,390)} & \cdots & \cdots & R_{(i,730)} \end{pmatrix}^T \quad (7)$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} \overline{X}_{380} & \overline{X}_{390} & \cdots & \cdots & \overline{X}_{730} \\ \overline{Y}_{380} & \overline{Y}_{390} & \cdots & \cdots & \overline{Y}_{730} \\ \overline{Z}_{380} & \overline{Z}_{390} & \cdots & \cdots & \overline{Z}_{730} \end{pmatrix} \cdot \begin{pmatrix} L_{380} & & & \\ & L_{390} & 0 & \\ & 0 & \ddots & \\ & & & L_{730} \end{pmatrix} \cdot \begin{pmatrix} R_{380} \\ R_{390} \\ \vdots \\ R_{730} \end{pmatrix} \quad (8)$$

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} & T & \end{pmatrix} \cdot \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (9)$$

$$(T) \begin{pmatrix} LS_{(R,380)} & LS_{(R,390)} & \cdots & \cdots & LS_{(R,730)} \\ LS_{(G,380)} & LS_{(G,390)} & \cdots & \cdots & LS_{(G,730)} \\ LS_{(B,380)} & LS_{(B,390)} & \cdots & \cdots & LS_{(B,730)} \end{pmatrix} \cdot \left[\begin{pmatrix} \overline{X}_{380} & \overline{X}_{390} & \cdots & \cdots & \overline{X}_{730} \\ \overline{Y}_{380} & \overline{Y}_{390} & \cdots & \cdots & \overline{Y}_{730} \\ \overline{Z}_{380} & \overline{Z}_{390} & \cdots & \cdots & \overline{Z}_{730} \end{pmatrix} \cdot \begin{pmatrix} L_{380} & & & \\ & L_{390} & 0 & \\ & 0 & \ddots & \\ & & & L_{730} \end{pmatrix} \right]^{-1} \quad (10)$$

Finally, a lookup-table is composed by calculation with Equation (10).

Results

The presumed characteristics and accuracy of calculation are shown as follows. The scanner, named "PS4800PRO", used here is manufactured by PFU in Japan.

Presumed Characteristics of R,G,B

The presumed characteristics of R,G,B are shown as follows:

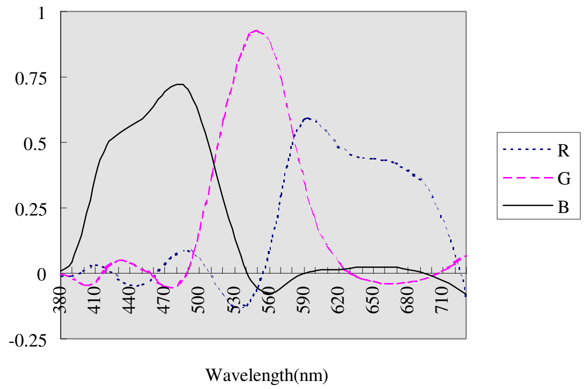


Figure 3. Presumed characteristics of R,G,B.

Judging from the independency and colors of each spectral characteristics, the proposed method by using SVD, mentioned here, seems effective to presume such characteristics. Such presumed characteristics are used to calculate the values output by scanners, and their effectiveness is ascertained by the smaller color differences shown below.

Comparison Between Measured and Calculated Values

Precision of calculation is shown here as comparison between the measured values of 288 color patches according to ISO 12641 and the simulated values interpolated by the look-up table composed based on the presumed characteristics of R,G,B. Only 24 color patches are used for presumption. Comparison is carried out by averaging/taking the maximum of the color differences between the measured and the interpolated values on 288 color patches according to ISO 12641. The results are summarized in Table 1.

Table 1. Comparison between color differences and average of color differences (Number: Average/Maximum; Unit: ΔE_{94})

	ISO 12641 (AGFA)	PM-800DC (EPSON)
New Method	1.5/8.0	2.5/6.7
Previous Method	1.5/11.2	2.2/18.0

The results show that the proposed method is as effective and have the same accuracy as the previous method, which composes look-up tables by linearly interpolating color values based only on 288 color patches mentioned above.

Moreover, it means that the presumed characteristics calculated above are practically effective and that the color gamut can be calculated mathematically based only on 24 color patches with fine precision.

Conclusion

This proposed method has been demonstrated to have following advantages:

(1) Similar accuracy of matching colors is achieved based on less color patches(about 20).
(2) This method is less influenced by difference of the color gamut of each scanner.
(3) It is very effective to estimate the color gamut of the scanner by this method.
(4) This method is very creative as the desired spectral characteristics of R,G,B can be presumed after some prototypes of scanners are tentatively made. In the near future, it is possible to presume such characteristics based only on design of a scanner.

Future Studies

The following studies are now scheduled.

(1) Nonlinear optimization will be applied to the above results in order to increase accuracy and to determine whether or not this solution is optimal.
(2) This method will be applied to the development of many kinds of scanner in order to verify its effectiveness.
(3) A similar method on a spectral data basis will be developed and applied to the other kinds of device in order to ascertain whether or not spectral color management is generalized.

References

1. George E. Forsythe, Michael A. Malcolm, Cleve B. Moler, Computer methods for mathematical computations, Prentice-Hall Inc., Englewood Cliffs, NJ, 1977
2. Noriyuki Shimano, Reconstruction of spectral characteristics of colours by image signals: Media independent reconstruction, J. Electronic Imaging, Vol. 24, No. 5, (1995).

Biography

Mr. Usui is a geophysicist graduated from Tohoku university in Japan. Since then, he has been engaged in exploration by image analysis. (Remote Sensing, Acoustic Sensing and so on) At the present, he is engaged in color management and developing the new soft proofing system at Fujitsu Laboratories LTD. He is also an expert of the IEC/TC100/PT61966 Part7(colour printer).