Vector Error Diffusion Method for Spectral Color Reproduction

Takayuki Kawaguchi, Norimichi Tsumura, Hideaki Haneishi, Masahiro Kouzaki, and Yoichi Miyake*

Department of Information and Image Sciences, Chiba University
Chiba, JAPAN

**Toyokawa Development Center, Minolta Co., Ltd.*
Nagoya, JAPAN

Abstract

A spectral color reproduction method is proposed based on a vector error diffusion method. A low-dimensional linear model is used to approximate reflectance spectra, and the vector error diffusion is performed in a score vector space of the linear model. A suitable set of primary colors is also selected from oil colors. Presented method performed better than conventional colorimetric vector error diffusion method for robust color reproduction for a change of illuminant.

Introduction

With the blooming of the network society, various images of such as products and fine art paintings[1] can be watched or appreciated at home by accessing digital archives. At these electronic museums or Internet shopping, it is necessary to reproduce correct colors considering the environmental illuminants around the viewers. Color correction techniques based on an estimation of reflectance spectra were proposed to reproduce correct color under an arbitrary environment[2-11]. The reflectance spectra are estimated from the multi-band images based on samples of reflectance spectra, which are measured previously. Using the estimated reflectance spectra and spectral characteristic of environmental illuminant, correct color is calculated and reproduced on a CRT monitor or hardcopy by colorimetrical color reproduction[6]. In the colorimetric color reproduction, the reproduced color depends on the environmental illuminant. Since the environmental illuminants will change with time, the calculation and reproduction must be repeated while the viewer is watching or appreciating the images. On a hardcopy, however, it is impossible to change the reproduced color after printing.

In this paper, a new digital halftoning method is introduced for a spectral color reproduction of the object. In a spectral color reproduction, reflectance spectra of hardcopy will be matched with those of original object. The proposing method is based on a vector error diffusion (VED) method[12-14] and a linear model of spectral reflectance[15].

Conventional Colorimetric Vector Error Diffusion Method

A conventional colorimetric VED method[12] is briefly described in this section. We define the eight colors; Cyan, Magenta, Yellow, Black, Red, Green, Blue, and White, as primary colors. In the VED method, all colors are given as colorimetrical colors, and the colors are treated by vectors in a three-dimensional colorimetrical color vector space such as XYZ and L*a*b*. Figure 1 shows the process of the VED method, where $\boldsymbol{f}_{x,y}$, $\boldsymbol{m}_{x,y}$, $\boldsymbol{v}_{x,y}$, and $\boldsymbol{e}_{x,y}$ denote vectors of objective color, corrected color, selected primary color, and error on the image coordinate (x, y), respectively. The error vector is calculated on the image coordinate (x, y) as follows,

$$\boldsymbol{e}_{x,y} = \boldsymbol{m}_{x,y} - \boldsymbol{v}_{x,y} \qquad (1)$$

and diffused into unprocessed neighboring pixels to keep correct color in a sense of averaged additive color mixture. This process is repeated pixel by pixel in a raster scan fashion over the entire image. From a different point of view, the corrected color is calculated from an objective color and the error vectors processed before.

$$\boldsymbol{m}_{x,y} = \boldsymbol{f}_{x,y} - \sum_{i,j} w_{i,j} \boldsymbol{e}_{x-i,y-j} \qquad (2)$$

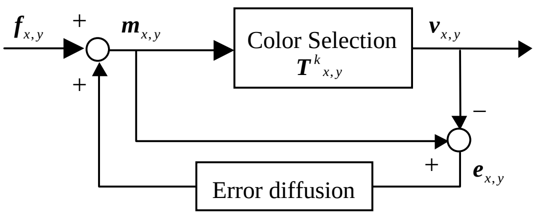


Figure 1. Process of vector error diffusion method

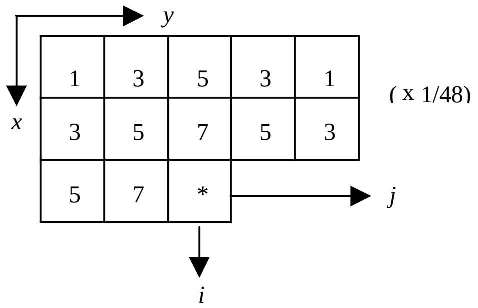


Figure 2. Weights proposed by Jarvis, Judice, and Ninke for the ED algorithm

where $w_{i,j}$ is the weight to diffuse the error from image coordinate (i, j) to (x, y). The typical weights originally used by Jarvis, Judice, and Ninke[16] are given in Fig. 2, and they are also used in this paper. The printed color is chosen from eight primary colors by the following equation.

$$\boldsymbol{v}_{x,y} = \arg\min_{\boldsymbol{T}_k} \| \boldsymbol{m}_{x,y} - \boldsymbol{T}_k \| \qquad (3)$$

where $\|\cdot\|$ denotes the Euclid norm of vector, and $\boldsymbol{T}_k$ (k= C, M, Y, K, R, G, B, W) denotes vectors of eight primary colors. Equation 2 means that the closest color to the corrected color is chosen from the primary colors in the color space.

In the conventional VED method, some smear is appeared at the boundary area of color. Since this smear is generated by the accumulated error from the colors out of gamut, this smear is prevented by gamut mapping techniques before applying the VED method. In practical devices, mechanical dot gain should be compensated, some techniques has been proposed for the compensation[13,14].

The color reproduced by conventional VED method is correct colorimetrically if the objective color is in the color gamut of devices and the mechanical dot gain is ignored. In this paper, the mechanical dot gain is ignored and the colors in the gamut and out of gamut are evaluated separately.

Spectral Vector Error Diffusion Method

Achieving a spectral color reproduction, reflectance spectra of hardcopy should be matched with those of original object. Therefore, the processing of VED must be performed in the vector space of spectral reflectance. However, it is difficult to process this high dimensional spectral data. A low dimensional approximation method[15] is used to reduce the dimension of the high dimensional data. Let $\boldsymbol{s}$ denote a

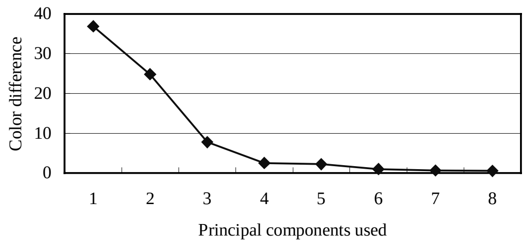


*Figure 3. L*a*b* color difference between original and approximated spectra*

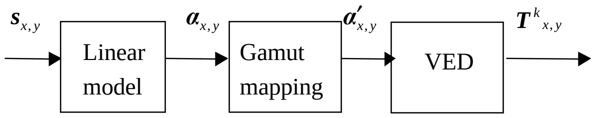


Figure 4. Spectral vector error diffusion method

column vector with 61 elements representing the spectral reflectance at interval of 5 nm from 400 nm to 700 nm. The vector of spectral reflectance can be approximated by *m*-dimensional linear model as follows,

$$\boldsymbol{s} = \sum_{i=1}^{m} \alpha_i \boldsymbol{p}_i \qquad (4)$$

$$\alpha_i = \boldsymbol{s}^T \boldsymbol{p}_i \qquad (5)$$

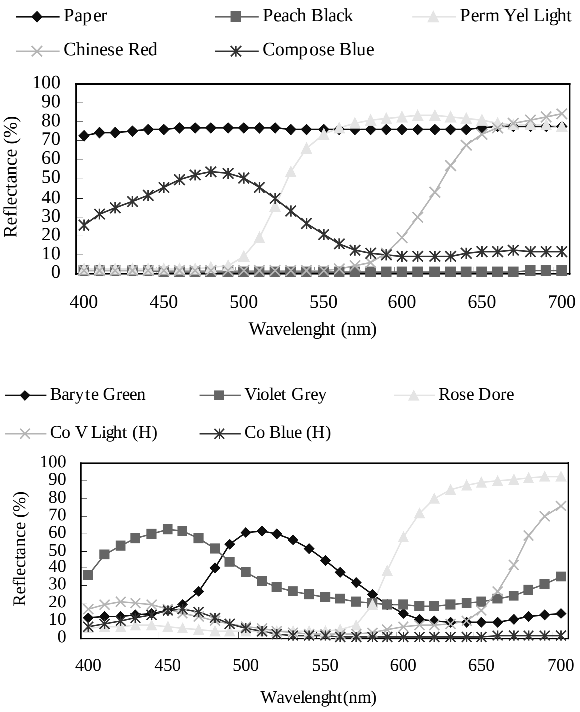
where $\boldsymbol{p}_i$ is the basis vector, α_i is the score for the basis vector $\boldsymbol{p}_i$. Equation 4 can be rewritten by using vector-matrix form as follows.

$$\boldsymbol{s} = \mathrm{P}\boldsymbol{\alpha} \qquad (6)$$

$$\mathrm{P} = [\boldsymbol{p}_1, \boldsymbol{p}_1, \cdots \boldsymbol{p}_m]$$
$$\boldsymbol{\alpha} = [\alpha_1, \alpha_1, \cdots \alpha_m]$$

where P is a basis matrix, and $\boldsymbol{\alpha}$ is a score vector. As the basis vectors, we used the principal component vectors which are obtained by analyzing the samples of natural reflectance spectra[17]. Figure 3 show the L*a*b* color difference between original and approximated spectra against the principal components used. From the Figure 3, it is seen that the four or five components are enough to reproduce the color within the just noticeable color difference.

Figure 4 shows the process of the spectral VED method. First, the low-dimensional linear approximation method is applied to the reflectance spectra of the object and primary colors, and the score vector for each spectral reflectance is obtained. Second, the gamut mapping is performed for the score vectors out of gamut. The color gamut is formed by the score vectors of primary colors in the vector space. Third, the conventional VED method is applied to the score vectors.



Figures 5. Ten reflectance spectra of selected primary colors

Table 1 RMS error (%)

Number of primary colors	Dimension of linear model	In gamut	Out of gamut
8	5	2.46	4.66
9	5	2.11	4.71
10	5	2.24	4.42
	6	1.87	4.41
	7	1.77	4.33
Colorimetric reproduction		5.83	7.27

Table 2 L*a*b* color difference

Num. of primary colors	Dimension of linear model	D50	Lupika DayC	Na Lamp	Neo Pua
8	5	6.93	8.89	6.54	6.25
9	5	6.57	8.45	6.12	5.97
10	5	5.92	7.33	5.48	5.38
	6	5.31	7.22	5.02	4.94
	7	5.31	7.13	5.05	4.85
Colorimetric reproduction		5.06	7.76	9.76	8.01

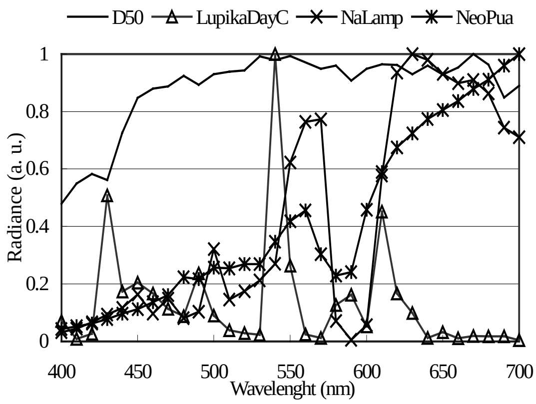


Figure 6. Illuminants used to evaluate the color difference

Selection of primary colors

Primary colors are selected for the spectral color reproduction considering the multiple ink devices. As the candidates of primary colors, we consider 145 oil colors (Holubein Artist's Oil Colors)[18]. The reflectance spectra are measure as follows. We used color patches painted on 4cm x 5cm film with the thickness of about 10 μm. The spectral radiant power of the 145 samples on a standard diffusing reflector was measured by a spectrophotometer (Abesekkei Model 2706) at the angle of 45 viewing condition with 2 viewing angle. The color patches were set under D65 illuminant in a standard illumination booth, and data were measured at intervals of 5nm from 400nm to 700nm. The spectral reflectance was calculated by dividing spectral reflectance of the color samples by the spectral reflectance of the standard diffusing reflector.

The precision of spectral color reproduction depends on both the linear approximation of objects and primary colors and the color differences caused by the gamut mapping. If the five dimensional approximation is used, the former is ignored and the latter is significant for the spectral color reproduction. Therefore, we define the evaluation value for the selection of primary colors based on the color differences in 24 reflectance spectra in Macbeth Color Checker as follows.

$$E = \sum_{i=1}^{24} \| \boldsymbol{\alpha}_i - \boldsymbol{\alpha}_i^{'} \| \tag{7}$$

where $\boldsymbol{\alpha}_i$ and $\boldsymbol{\alpha}_i^{'}$ denote the original and mapped score vectors. However, it is impossible to evaluate all combinations of 145 oil colors. We selected the primary colors step by step as follows.

Step 1 Spectral reflectance of paper is selected as a primary color.
Step 2 One more spectral reflectance that gives the minimum evaluation value is selected from the rest of oil colors.
Step 3 The procedure is repeated between Step 2 and 3 until the decided number of colors is selected.

Figures 5 show the 10 reflectance spectra of the selected primary colors.

Computer Simulation for Evaluation of the Spectral VED Method

Using the selected primary colors, the precision of spectral color reproduction is evaluated by computer simulation using the spectral image of Macbeth Color Checker where the 24 kinds of reflectance spectra are included. Tables 1 and 2 show the RMS error and L*a*b* color difference compared with the objective color. Figure 6 show the illuminant used to evaluate the color difference. The colors in and out of gamut are separately evaluated in Table 1. The dimension of the linear model is set as five for eight and nine primary colors, five to seven for ten primary colors. For the comparison, the RMS error and color difference by the colorimetric VED method are also shown in Tables. It is found that the spectral color reproduction improves the color reproduction of hardcopy under an arbitrary illuminants.

Conclusion

A spectral vector error diffusion method was proposed based on a conventional vector error diffusion method. Five to seven dimensional linear models were used to approximate reflectance spectra. Ten suitable sets of primary colors were selected from oil colors, and the presented method performed better than conventional colorimetric vector error diffusion for spectral color reproduction.

References

1. K. Martinez and A. Hamber, "Towards a colorimetric digital image archive for the visual arts," Proc. SPIE 1073, pp.114-121 (1989).

2. B.A. Wandell, "The Synthesis and Analysis of Color Images," IEEE Trans. PAMI PAMI-9, pp.2-13 (1987).

3. M.J. Vrhel and H.J. Trussell, "Color Correction Using Principal Components," Color Res. Appl. 17 , pp.328-338 (1992).

4. T. Shiobara, S. Zhou, H. Haneishi, N. Tsumura and Y. Miyake, "Improved color reproduction of electronic endoscopes" J. Imag. Sci. and Tech. 40, pp.494-501 (1996).

5. H. Maitre, F. Schmitt, J.-P. Crettez, Y. Wu and J.Y. Hardeberg: IS&T/CIC 4^{th} Color Imaging Conference, p.50 (1996).

6. F. H. Imai, N. Tsumura, H. Haneishi, Y. Miyake, "Prediction of color reproduction for skin color under different illuminants based on the color appearance models", J. Image Science and Technology 41, 2, pp.166-173(1997).

7. H. Haneishi, T. Hasegawa, N. Tsumura and Y. Miyake: "Design of color filters for recording art works," Proc. of IS&T's 50th Annual Conference, pp.369-372 (Boston, 1997).

8.Y. Yokoyama, N. Tsumura, H. Haneishi, and Y. Miyake, J.. Hayashi, M. Saito, "A new color management system based on human perception and its application to recording and reproduction of art printing," IS&T/SID's 5th Color Imaging Conference, pp.169-172(1997).

9. M. Yamaguchi, R. Iwama, Y. Ohya, T. Ohyama, Y. Komiya, "Natural color reproduction in the television system for telemedicine," Proc. SPIE 3031, pp.482-489 (1997).

10. H. Haneishi, T. Iwanami, N. Tsumura, and Y. Miyake, "Goniospectral imaging of 3D objects," IS&T/SID's 6th Color Imaging Conference, pp. 173-176(1998).

11. F. H. Imai and R. S. Berns, "High-Resolution Multi-Spectral Image Archives: IS&T/SID's 6th Color Imaging Conference, pp.224-227(1998).

12. H.Haneishi, T.Suzuki, N.Shimoyama, Y.Miyake. "Color digital halftoning taking colorimetric color reproduction into account", Journal of Electronic Imaging 5, 1, pp.97-106 (1996).

13. C. Kim, S. Kim, Y. Seo, I. Kweono. "Model Based Color Halftoning Techniques On Perceptually Uniform Color Spaces", IS&T's 47th Annual Conference, pp.15-20 (1994).

14. S. Wang. "Algorithm-Independent Color Calibration for Digital Halftoning" The Fourth IS&T/SID Color Imaging Conference, pp.75-78(1996).

15. L.T. Maloney, "Evaluation of linear models of surface spectral reflectance with small numbers of parameters," Journal of the Optical Society of America A 3, pp.1673-1683 (1986).

16. J. F. Jarvis, C. N. Judice, and W. H. Ninke, "A survey of techniques for the display of continuous tone pictures on bilevel displays," Computer Graphics and Image Processing 5, pp.13-40(1976).

17.M.J. Vrhel, R. Gershon and L.S. Iwan, "Measurement and Analysis of Object Reflectance Spectra," Color Res. Appl. 19, pp. 4-9 (1994).

18. N.Tsumura, H. Sato, T. Hasegawa, H. Haneishi, and Y. Miyake, "Limitation of color samples for spectral estimation from sensor responses in fine art painting", Optical Review 6 (1999). (in press)