High Precision Color Masking in Sub-divided CIELAB Polar Coordinates Spaces

Atsumi Ishige, Hiroaki Kotera, and Chen Hung-Shing
Graduate School of Science and Technology, Chiba University, Chiba, Japan

Abstract

Variety of color masking technologies have been applied for hardcopies to correct the cross talks caused by unwanted absorption in colorants. Nonlinear color masking technology has been conveniently applied to reduce the reproduction errors on color printers. The color reproduction accuracy is expected to be furthermore improved when the masking matrices are optimized in sub-divided smaller color spaces than in whole color space.

This paper proposes a new method to improve the color masking accuracy for hardcopies. Here the input color space is partitioned into numbers of sub-spaces divided by radius, hue angle, chrominance, or others in CIELAB space so that each sub space equally includes the color chip samples inside the printer gamut. Linear or nonlinear color masking functions are applied to each sub-divided space and the masking coefficients are optimized individually by the method of least squares. The new method resulted in the high precision color matching with rms color differences ΔE_{ab}^{*}(rms) $\approx$ *1.5* for inkjet printer. As compared with conventional linear or nonlinear color masking methods, the color reproduction errors could be extremely reduced.

Introduction

Construction of color management system to reproduce accurate colors across the different media is important subject with the rapid spreads of electronic color imaging in recent years. Color correction technologies have been applied for hardcopies to eliminate the cross talks caused by unwanted absorption in colorants. Nonlinear color masking technology has been conveniently applied to reduce the reproduction errors on color printers. The color reproduction accuracy is expected to be furthermore improved when the transform matrices are optimized in sub-divided smaller color spaces than in whole color space.

This paper discusses the partitioning method of input color space into sub-spaces, where equal number of the color chip samples are included inside the device gamuts. Linear or nonlinear color masking functions are applied to each sub-divided space and the transform matrices are optimized individually by the method of least squares.

In the following sections, the performance of proposed method is compared with conventional color masking methods.

System Model

A color printer is modeled as a forward transform from input signal X to tristimulus value T_o, while the color corrector is designed to work as its inverse transformer from T_i to X as shown in *Fig. 1*. Tristimulus value T_i is converted to RGB density before color masking.

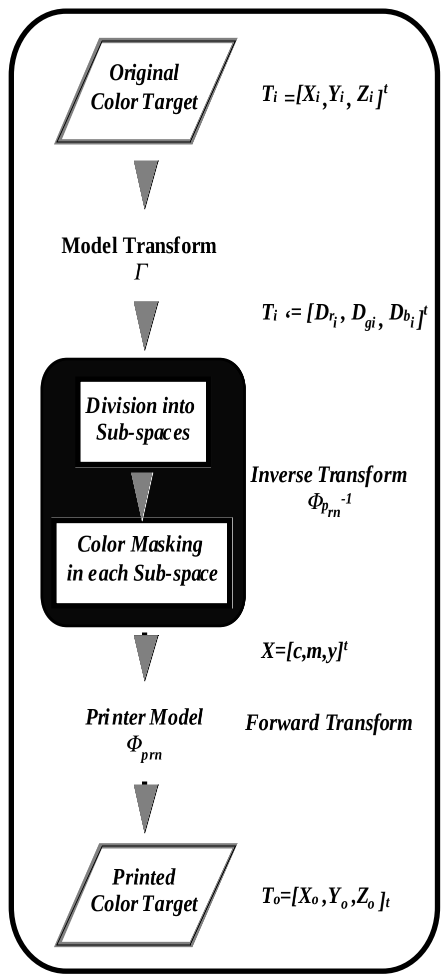

Figure 1. System model

- Forward transform

$$T_o = \Phi_{prn}(X) \quad (1)$$

- Inverse transform of printer

$$X = \Phi_{prn}^{-1}(T_i') \quad (2)$$

$\Phi_{prn}^{-1}(T_i)$ is approximated by a polynomials of T_i.

- Model transform

$$T_i' = \Gamma(T_i) \quad (3)$$

$\Gamma(T_i)$ includes 3×3 linear matrix and logarithmic transforms.

Sub-space Model

Fig. 2~Fig. 5 show the partitioning methods of the color space into plural number of sub spaces. A most simple way is to divide the each axis by equal interval where the sub-space is formed by tri-linear box as shown in *Fig. 2*. However the printed sample color targets are not distributed uniformly inside the gamut of actual color printers and the equally divided sub-spaces don't include the same number of sample points in each sub-space.

In the conventional tri-linear division, CIELAB space is partitioned into cubic sub-spaces along L*, a* and b* axes. Here, the enough sample numbers to determine the color masking coefficients are not always guaranteed.

Fig. 3 shows one-dimensional LAB vector division, where CIELAB color space is partitioned into N sub-space by LAB vector magnitudes.

Fig. 4 illustrates the two-dimensional luminance-chrominance (LC) division, where CIELAB color space is partitioned into *M* x *N* sub-spaces along the following two directions.

[1] M divisions in L* direction;

$$L^*_j \geq \Delta L^*_j \geq L^*_{j-1};\ j=1{\sim}M \quad (4)$$

[2] N divisions in C* direction;

$$C^*ab_k \geq \Delta C^*ab_k \geq C^*ab_{k-1};\ k=1{\sim}N \quad (5)$$

Here the boundary luminance L^*_j and chroma $C^*_{ab_k}$ are determined to include the constant sample points in a sub-space area divided by ΔL_j and $\Delta C^*_{ab_k}$ for $j=1{\sim}M$ and $k=1{\sim}N$ in CIELAB space.

Fig. 5 illustrates the polar coordinates division, where CIELAB color space is partitioned into *M* x *N* sub-spaces along the following two directions.

[3] M divisions in hue angle direction;

$$\theta_j \geq \Delta\theta_j \geq \theta_{j-1},\ \theta = \tan^{-1}(b^*/a^*);\ j=1{\sim}M \quad (6)$$

[4] N divisions in radial direction of LAB vector;

$$r_k \geq \Delta r_k \geq r_{k-1},\ r=\{L^{*2}+C^{*2}_{ab}\}^{1/2},\ C^*_{ab}=\{a^{*2}+b^{*2}\}^{1/2};\ k=1{\sim}N \quad (7)$$

Here the sector angle θ_j and radius r_k are determined to include the constant sample points in a sub-space area surrounded by $\Delta\theta_j$ and Δr_k for $j=1{\sim}M$ and $k=1{\sim}N$ in CIELAB space.

Experimental Results

These models have been tested for color inkjet printer. Totally $8^3=512$ color samples were printed on the printer driven by cmy signals $X_i=[c_i,m_i,y_i]^t$ and their tristimulus values $T_o=[X_o,Y_o,Z_o]^t$ were measured by spectro-colorimeter. The color masking matrices to realize inverse transform from $\boldsymbol{T}$ to $\boldsymbol{X}$ are calculated by using these data set $\{\boldsymbol{X}_i,\boldsymbol{T}_o\}_{i,o=1\sim512}$.

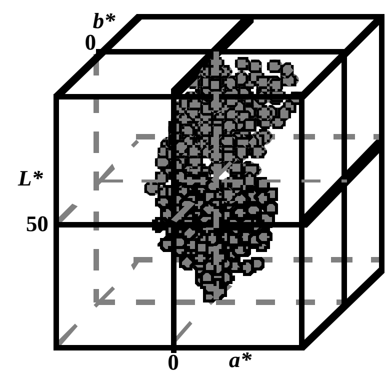

Figure 2. Tri-linear division

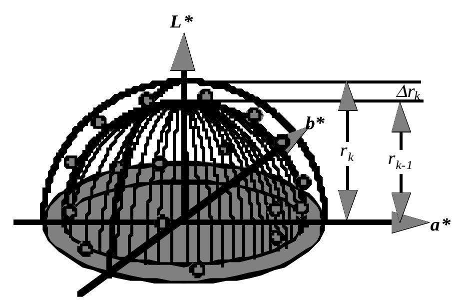

Figure 3. LABvector division

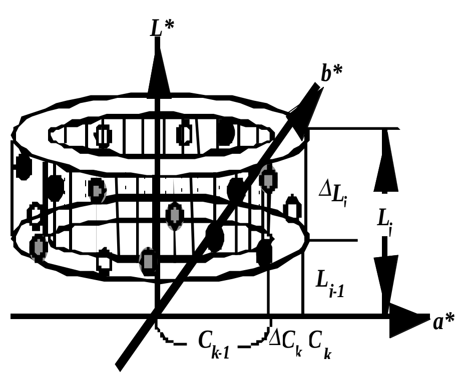

Figure 4. LC division

In the tri-linear division, CIELAB space were segmented into eight cubes with boundaries in *a*=0, b*= 0, and L*=50*. Thus, the numbers of color samples included in each sub-space were uneven.

In LAB vector division, CIELAB space were segmented into $N=2\sim128$ radial segments by $\{\Delta r_k\}_{k=1\sim128}$. Thus, whole color sample space is divided into $2\sim128$ sub-spaces including equal number of samples in each.

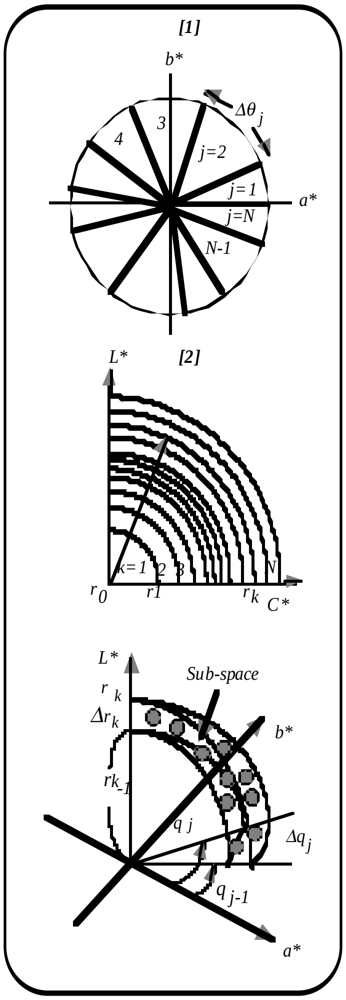

Figure 5. Polar coordiantes division

Also in LC division, whole color sample space is divided into $4\sim128$ sub-spaces according to two-dimensional L* and C* segmentations.

In the polar coordinates division, the distributions of color sample values $LAB_i=[L^*_i,a^*_i,b^*_i]^t$, were first segmented into $M=2\sim64$ hue angle sectors where $3\mathrm{x}N$ masking coefficients are possible to be determined.

Fig. 6 shows RMS color difference for trained target colors without division, Tri-linear division, LAB vector division and Polarcoodinates division, respectively. Except without division, LAB space is divided in to 8 sub-spaces and linear or non-linear color masking functions are applied to each sub-space and the transform matrices are optimized individually by the method of least squares. The color differences in Fig. 6 have been estimated by using the trained color patches. The best reproduction was obtained by LAB vector division with 3rd order masking, resulting $\Delta E_{ab}*(rms)\approx1.5$.

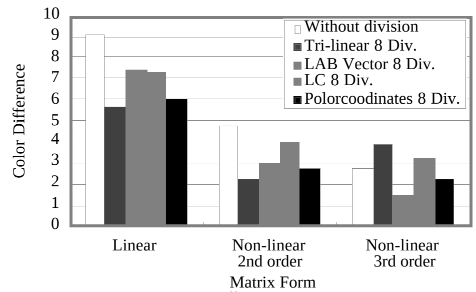

Fig.6 RMS color difference (Trained target color)

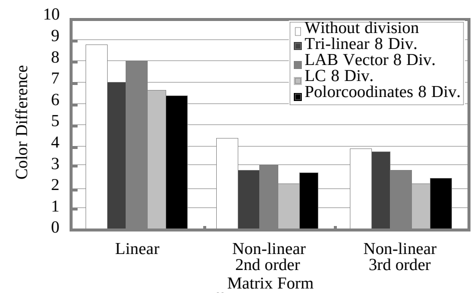

Fig.7 RMS color difference (Non-trained target color)

Fig. 7 shows RMS color differences for non-trained targets. The same divisions and the same matrices as in *Fig. 6* are used for the calculations. In the estimation for non-trained targets, the best reproduction was obtained by LC division with 3rd order masking, resulting $\Delta E_{ab}*(rms)\approx2.1$.

As clearly shown, the method with sub-space division resulted in higher precision color matching than the conventional method without division.

Both *Fig. 6* and *Fig. 7* show that the results of LC division and Polar coordinates division seem to be more stable, while LAB vector division gives excellent results in spite of one-dimensional division.

Fig. 8 shows the reproduced color maps in a*-b* plane. It is shown that the sub-space division methods result in high precision color matchings to the original.

Discussion and Conclusion

The higher precision color masking has been approached by the optimization in sub-divided color spaces. Non-uniform division to sub-spaces, including the equal number of color samples in each, makes it possible to use the higher order of color masking and resulted in high precision reproductions with $\Delta E_{ab}*(rms)\leq2$ for inkjet printer. As compared with conventional color transforms by single matrix, the color errors in the proposed methods could be reduced to two third or less inside the device gamuts.

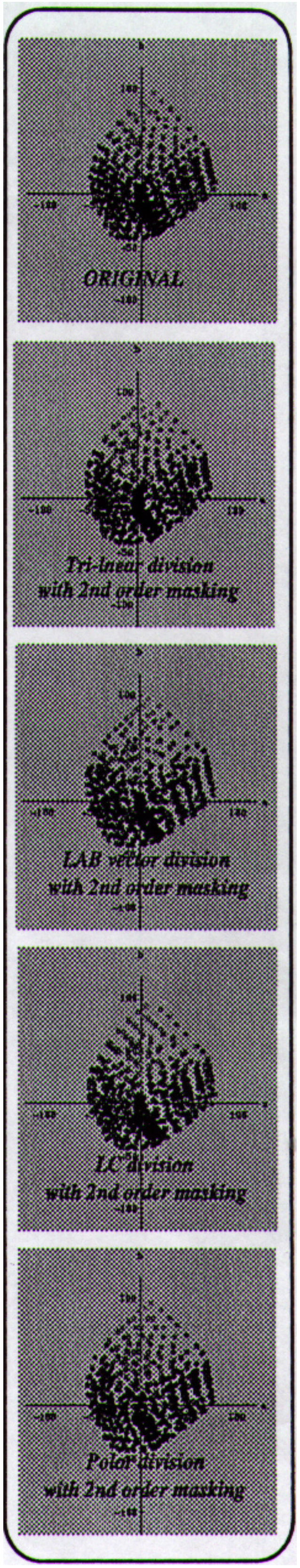

Figure 8. Distribution of color chips reproduced by inkjet printer

In the Tri-linear division, the best result was given by 2nd order masking, while RMS color difference is increased for 3rd order masking. This may be caused by the unevenness of color sample numbers in each sub-spaces. Moreover, in the uniform divisions, the sufficient sample numbers can't be guaranteed enough to decide the higher order masking coefficients when the number of sub-divisions increases.

Polar coordinates division in the hue angle and radial directions, is considered to be more stable in both trained and non-trained estimations, because the sub-space surrounded by $\Delta\theta_j$ and Δr_k will include the color samples resemble in hue and colorfulness and the spherical boundary can cover the printer gamut more reasonably. It resulted in $\Delta E_{ab}^*(rms) \approx 2.4$ for trained targets and $\Delta E_{ab}^*(rms) \approx 2.2$ for non-trained target with 3rd order masking.

LAB vector division with 3rd order masking resulted in the highest reproduction with $\Delta E_{ab}^*(rms) \approx 1.5$ for trained targets, and LC division with 3rd order masking resulted in the highest reproduction with $\Delta E_{ab}^*(rms) \approx 2.1$ for non-trained targets.

These values are almost approaching to the mechanical stability about $\Delta E_{ab}^*(rms) \approx 1.0$ in inkjet printer.

The gamut compression process is needed for the inputs outside the gamut and is under development. Image device, such as scanner, digital camera, monitor or others, has larger gamuts than inkjet printer.

References

1. H. Kotera, "Color Rendition in Digital Printing", *JIIEEJ*, **14**, 5, p.298-307 (1985)
2. H. Ikegami, OELASE '89, *SPIE*, Los Angeles, 1075-1105 (1989)
3. A. Ishige, R. Saito, H. Kotera, "High quality color management with polar coordinates division of L*a*b* space", PROCEEDING OF THE 1998 IEICE GENERAL CONFERENCE, EIC, D-11-188 (1998)

Biography

Atsumi Ishige received the BS degree in Image Science from Chiba University in 1997. He is a student at Graduate School of Science and Technology, Chiba University. His current interests include color reproduction, gamut mapping, and color management technologies for multi-media.