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Color Conversion Technology of Four-Primary Color Images Developed on Wide Color Gamut Red, Green, Blue Monitor

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Abstract. *To assist with the color system design of a four-primary color display, it is necessary to build up a four-primary color simulation platform displayed on a wide color gamut red, green, blue (RGB) monitor. A new four-primary color conversion algorithm that is able to simulate four-primary color appearance built on a wide color gamut RGB monitor is proposed. The designed four-primary color system is composed of red, green, blue primary colors based on sRGB standard and the addition of the fourth primary color. The simulated fourth primary colors are selected from Kodak Wratten color filters, which CIE u′ v′ chromaticity coordinates are located in the range between the sRGB triangle gamut and the Adobe RGB (1998) triangle gamut. The four-primary color conversion algorithm is designed to be implemented on the Adobe RGB (1998) platform to simulate four-primary color appearance. The linear programming to formulate the convex optimization problem, which is named linear color convex combination, is introduced to establish a color conversion algorithm between the four-primary color signal and the corresponding color stimulus. The four-primary color conversion is also applied to build up four-color separation channels, which can simulate four-color channels shown on the Adobe RGB (1998) platform. It is demonstrated that the proposed color conversion algorithm can perform well on four-color channels displayed on the Adobe RGB (1998) platform. Meanwhile, the optimal four-color signals can be determined according to the tonal smoothness evaluation based on edge detection by Prewitt or Sobel operation. © 2009 Society for Imaging Science and Technology.*
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INTRODUCTION

The development of wide color gamut (WCG) display plays an important role in the development of high-quality television. Multiprimary color LCDs with more primary colors (i.e., more than three) is one of the useful technologies to approach a WCG display. In the current display system, all color images are recorded and transformed by the three-primary color system. To develop a four-primary color system, it is necessary to develop a color conversion model between the three-primary and four-primary color systems.

Several important color conversion algorithms for designing multiprimary color display systems are available. Ajito et al. developed the matrix switching method.[1] It splits the color gamut of multiprimary display into pyramidal units in *XYZ* color space. Although this method has high efficiency, the color signals cannot switch smoothly at the boundary between a pair of pyramids. Motomura et al. proposed the linear interpolation on equiluminance plane method (LIQUID) method based on linear interpolation on an equiluminance plane.[2] It performs linear interpolation on luminance and saturation axes concurrently. This method produces smoother tones than the matrix switching method when hue is switched. König et al. proposed the metameric black method.[3] This method yields smoother tones than the LIQUID and matrix switching methods when color gradations are displayed.[3] Meanwhile, Eliav et al. introduced the guideline for choosing color filters in a four-color configuration.[4] They suggested that the addition of yellow can enhance the luminance and allow flexibility in the chromaticity of the green primary.[4]

In this article, a new four-primary color conversion model based on linear programming to formulate the convex combination problem, which is named linear color convex combination (“L3C”), is proposed. It is easily introduced into a wide color gamut red, green, blue (RGB) monitor to simulate the four-primary color channels of a color image.

DEVELOPMENT OF A FOUR-PRIMARY COLOR SYSTEM

Figure 1 demonstrates the color conversion workflow for transferring from a three-primary color system to a four-primary color system. First, all pixels of input three-primary color image are converted to the corresponding color stimulus values according to the sRGB standard.[5] The tristimulus values of each pixel in an image will be converted into four-color signals using the proposed color conversion algorithm, then four-color channels will be created on the Adobe RGB (1998) platform.[6]

In traditional color science theory, Grassmann’s law is used to express any additive color mixture that could be matched by a linear combination of the proper amounts of

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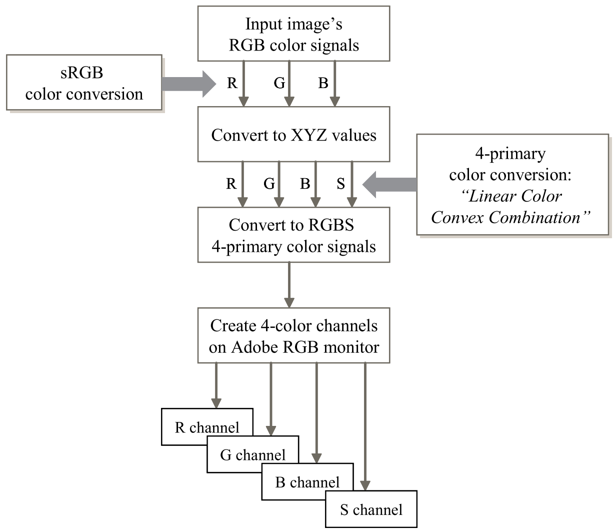


Figure 1. Color conversion operation from three-primary colors to four-primary colors (forward conversion).

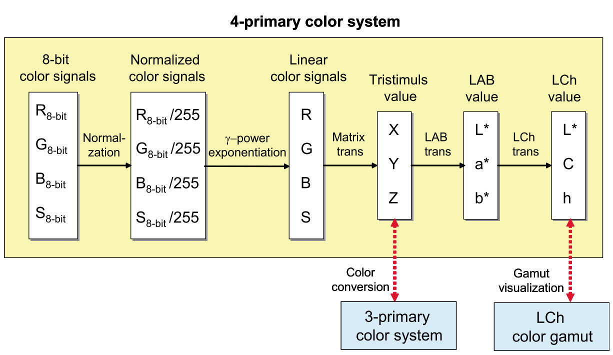


Figure 2. Color transformation flow in a four-primary color system.

three-primary color stimuli.[7] In this article, Grassmann's law is extended to the four-primary color system. Thus it is assumed that there exists a linear transformation between linear four-primary color signals (i.e., γ-corrected four-primary color signals) and corresponding color tristimulus values in the four-primary color system.

Similar to the three-primary color system based on sRGB standard,[5] the color transformation of the four-primary color system in this article is described as shown in Figure 2. It consists of normalization, γ-power exponentiation, matrix transformation, LAB transformation, and *LCh* transformation. A set of tristimulus value *XYZ* in such a system can be regarded as a colorimetric connection space to achieve the same color rendering ability as the three-primary color system, and *LCh* values are used to perform three-dimensional (3D) color gamut visualization.

In addition, an Adobe RGB (1998) monitor is utilized to simulate four-color channels. The designed four-primary color system is composed of red, green, and blue colors (i.e., [R], [G], and [B]) and the addition of fourth primary color [S]. The colorimetric coordinates of three-primary colors [R], [G], and [B] are designed to be the same as the sRGB

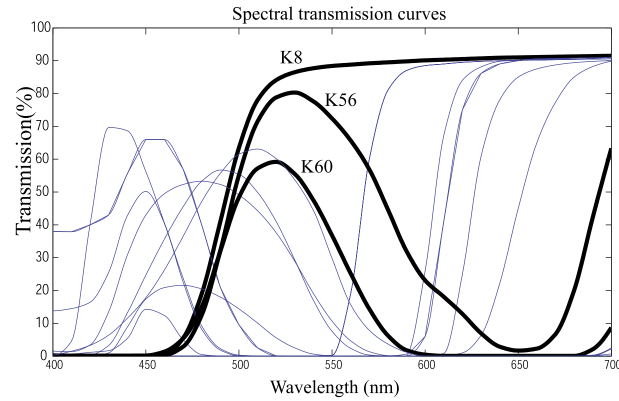


Figure 3. Spectral transmission curves of testing Kodak Wratten filters.

Table I. CIE *xy* chromaticity coordinates of test Kodak Wratten filters.

Primary colors	Color index	Chromaticity coordinates *x*	*y*	Color name
First primary	R_{sRGB}	0.6401	0.3300	Red
Second primary	G_{sRGB}	0.3000	0.6000	Green
Third primary	B_{sRGB}	0.1500	0.0600	Blue
	Kodak No. 8 (K8)	0.4306	0.5134	Yellow
	Kodak No. 15 (K15)	0.4989	0.4941	Yellow
	Kodak No. 22 (K22)	0.5988	0.3955	Yellow-red
	Kodak No. 31 (K31)	0.3977	0.1674	Magenta
	Kodak No. 32 (K32)	0.3197	0.1387	Magenta
Fourth primary (number=12)	Kodak No. 33 (K33)	0.5211	0.2061	Magenta
	Kodak No. 34A (K34A)	0.2073	0.0482	Magenta-blue
	Kodak No. 44 (K44)	0.1201	0.2905	Cyan
	Kodak No. 45A (K45A)	0.1291	0.1320	Cyan-blue
	Kodak No. 56 (K56)	0.3265	0.5887	Green
	Kodak No. 60 (K60)	0.2047	0.6235	Cyan-green
	Kodak No. 64 (K64)	0.1587	0.4277	Cyan

standard, while the candidate fourth primary color [S] is selected from the spectral transmission data of 12 Kodak Wratten color filters (i.e., K8, K15, K22, K31, K32, K33, K34a, K44, K45, K56, K60, and K64; where the prefix "K" means Kodak Wratten color filter. For example, K8 denotes Kodak Wratten No. 8 filter).[8] The spectral transmission curves (400–700 nm) of test color filters are shown in Figure 3. Under condition of D_{65} illumination and 2° *XYZ* color matching functions, their CIE *xy* and CIE $u'v'$ colorimetric values are calculated and arranged in Table I and Figure 4, respectively.

To simulate four-color image appearance on the Adobe RGB (1998) platform, the candidate fourth primaries [S] are selected from Kodak Wratten color filter data, with corresponding CIE $u'v'$ colorimetric values limited to those lying between the sRGB and the Adobe RGB (1998) color gamuts.

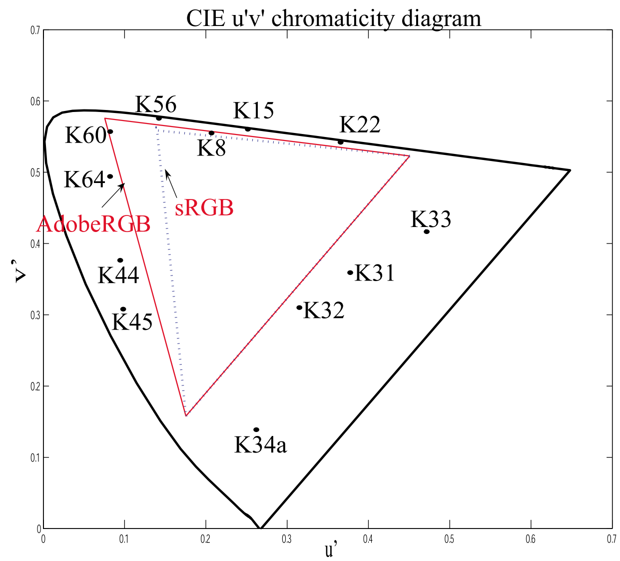


Figure 4. CIE $u'v'$ chromaticity coordinates of test Kodak Wratten filters.

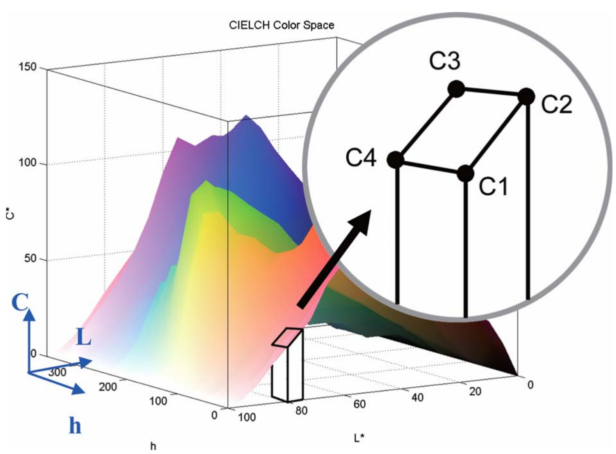


Figure 5. The formation of *LCh* gamut volume calculation.

As a result, K60, K56, and K8 can satisfy the above CIE $u'v'$ gamut condition. Because the colorimetric combinations based only on the CIE $u'v'$ diagram lack lightness information, it is difficult to judge which color is out-of-gamut or in-gamut exactly. Therefore, it is necessary to further analyze the selected colors in 3D *LCh* color space.

3D *LCh* COLOR GAMUT

The concept of 3D *LCh* gamut volume calculation is shown in Figure 5. The *LCh* gamut volume can be regards as the summation of $\Delta L \Delta h C$. When lightness interval is set to $\Delta L = 1$, hue interval is set to $\Delta h = 1°$, the boundary chroma value C can be defined as the average of four corresponding boundary chroma values: C_1, C_2, C_3, and C_4 as given in Eq. (1),

$$C = (C_1 + C_2 + C_3 + C_4)/4. \quad (1)$$

The *LCh* gamut volume V_{LCh} is further calculated by the summation of boundary chroma value $C_{i,j}$ in the *i-by-j Lh* segment, where $1 \leq i \leq 99$ with Δi interval 1; $1 \leq j \leq 360$ with Δj interval 1,

$$V_{LCh} = \sum C_{i,j}. \quad (2)$$

Design of Color Conversion Algorithm

Basically, the color description of a general four-primary color system can be regarded as the sum of three kinds of light emitting components [see Eqs. (3) and (4)]: (a) the mixed colors directly emitted from the color monitor {i.e., $M \times [\mathrm{R\ G\ B\ S}]^T$}, (b) the internal flare due to the flat panel's light leakage {i.e., $[X\ Y\ Z]^T_{\text{internal-flare}}$}, and (c) the external ambient flare from the panel surface glass {i.e., $[X\ Y\ Z]^T_{\text{external-flare}}$}. The superscript "$T$" in this article denotes the transportation of a matrix.

In Eqs. (3) and (4), $[X\ Y\ Z]$ is the normalized tristimulus value of the color mixture; M is the 3×4 matrix, which includes the normalized four-primary tristimulus values $[X_i\ Y_i\ Z_i]$ ($i = \mathrm{R,G,B,S}$). Meanwhile, [R G B S] represents the linear four-primary color signal amounts. Each element of [R G B S] should be limited within the range of $0-1$. It can be further represented by the γ-power functions of its corresponding 8-bit normalized color signals, $\mathrm{R_{8\text{-}bit}}$, $\mathrm{G_{8\text{-}bit}}$, $\mathrm{B_{8\text{-}bit}}$, $\mathrm{S_{8\text{-}bit}}$ [see Eq. (5)],

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M \begin{bmatrix} \mathrm{R} \\ \mathrm{G} \\ \mathrm{B} \\ \mathrm{S} \end{bmatrix} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{internal-flare}} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{external-flare}}, \quad 0 \leqq \mathrm{R,G,B,S} \leqq 1, \quad (3)$$

$$M = \begin{bmatrix} X_\mathrm{R} & X_\mathrm{G} & X_\mathrm{B} & X_\mathrm{S} \\ Y_\mathrm{R} & Y_\mathrm{G} & Y_\mathrm{B} & Y_\mathrm{S} \\ Z_\mathrm{R} & Z_\mathrm{G} & Z_\mathrm{B} & Z_\mathrm{S} \end{bmatrix}, \quad (4)$$

$$\begin{bmatrix} \mathrm{R} \\ \mathrm{G} \\ \mathrm{B} \\ \mathrm{S} \end{bmatrix} = \begin{bmatrix} (\mathrm{R_{8\text{-}bit}}/255)^{\gamma_\mathrm{R}} \\ (\mathrm{G_{8\text{-}bit}}/255)^{\gamma_\mathrm{G}} \\ (\mathrm{B_{8\text{-}bit}}/255)^{\gamma_\mathrm{B}} \\ (\mathrm{S_{8\text{-}bit}}/255)^{\gamma_\mathrm{S}} \end{bmatrix}. \quad (5)$$

If light emitting components of (b) and (c) of a general four-primary color system are rather small and near zero, the color description of an "ideal" four-primary color system can be formulated as given in Eq. (6). To focus on the development of the four-color conversion algorithm, the method proposed in this article will attempt to perform color conversion between an ideal three-primary color system and an ideal four-primary color system.

To closely match the color temperature and tone characteristics of the sRGB monitor, the white point and γ values [i.e., γ_R, γ_G, γ_B, and γ_S in Eq. (5)] of an ideal four-primary color system in this article are set to 6500 K and 2.2, respectively,

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M \begin{bmatrix} \mathrm{R} \\ \mathrm{G} \\ \mathrm{B} \\ \mathrm{S} \end{bmatrix}; \quad 0 \leqq \mathrm{R,G,B,S} \leqq 1. \tag{6}$$

Because the matrix M in the above equation is not symmetrical, the linear color convex combination (i.e., "L3C") method is applied to find the optimal linear color signal solutions [R G B S], when $[X\ Y\ Z]$ values are given in advance.

Basically, the convex combination problem is a kind of mathematical optimization problem in which the objective and constraints are convex.[9] In this article, the optimization of linear four-primary color signals can be transformed into the form similar to convex combination problems. Therefore, four "slack" linear color signal variables $[\mathrm{R}'\ \mathrm{G}'\ \mathrm{B}'\ \mathrm{S}']$ and equality constraints are introduced into the original algorithm according to the definitions of Eqs. (7)–(10),

$$\mathrm{R} + \mathrm{R}' = 1, \quad \text{where } 0 \leqq \mathrm{R}' \leqq 1, \tag{7}$$

$$\mathrm{G} + \mathrm{G}' = 1, \quad \text{where } 0 \leqq \mathrm{G}' \leqq 1, \tag{8}$$

$$\mathrm{B} + \mathrm{B}' = 1, \quad \text{where } 0 \leqq \mathrm{B}' \leqq 1, \tag{9}$$

$$\mathrm{S} + \mathrm{S}' = 1, \quad \text{where } 0 \leqq \mathrm{S}' \leqq 1. \tag{10}$$

Furthermore, the new condition between eight linear color signal variables $[\mathrm{RGBSR'G'B'S'}]$ and the tristimulus matrix $[X\ Y\ Z\ 1\ 1\ 1\ 1]$ can be established by the expressions of Eqs. (11) and (12), where N is a 7×8 matrix,

$$[X\ Y\ Z\ 1\ 1\ 1\ 1]^T = N[\mathrm{R\ G\ B\ S\ R'\ G'\ B'\ S'}]^T, \tag{11}$$

$$N = \begin{bmatrix} X_\mathrm{R} & X_\mathrm{G} & X_\mathrm{B} & X_\mathrm{S} & 0 & 0 & 0 & 0 \\ Y_\mathrm{R} & Y_\mathrm{G} & Y_\mathrm{B} & Y_\mathrm{S} & 0 & 0 & 0 & 0 \\ Z_\mathrm{R} & Z_\mathrm{G} & Z_\mathrm{B} & Z_\mathrm{S} & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix}. \tag{12}$$

It becomes a convex combination problem which must satisfy

$$\begin{aligned} &\text{min: (the tonal discontinuities of four-} \\ &\quad \text{primary color tones)} \\ &\text{subject to: the constraints of Eqs. (7)–(12).} \end{aligned} \tag{13}$$

If each element of matrix $[\mathrm{R\ G\ B\ S\ R'\ G'\ B'\ S'}]$ in Eq. (11) is set to zero in turn, eight basic linear color signal solutions V_i $(i=1-8)$ can be obtained. For example, if R is set to 0, Eqs. (11) and (12) will combine as follows:

$$\begin{bmatrix} X_\mathrm{R} & X_\mathrm{G} & X_\mathrm{B} & X_\mathrm{S} & 0 & 0 & 0 & 0 \\ Y_\mathrm{R} & Y_\mathrm{G} & Y_\mathrm{B} & Y_\mathrm{S} & 0 & 0 & 0 & 0 \\ Z_\mathrm{R} & Z_\mathrm{G} & Z_\mathrm{B} & Z_\mathrm{S} & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ \mathrm{G} \\ \mathrm{B} \\ \mathrm{S} \\ \mathrm{R}' \\ \mathrm{G}' \\ \mathrm{B}' \\ \mathrm{S}' \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}. \tag{14}$$

Then the above equation can be simplified to Eq. (15)

$$\begin{bmatrix} X_\mathrm{G} & X_\mathrm{B} & X_\mathrm{S} & 0 & 0 & 0 & 0 \\ Y_\mathrm{G} & Y_\mathrm{B} & Y_\mathrm{S} & 0 & 0 & 0 & 0 \\ Z_\mathrm{G} & Z_\mathrm{B} & Z_\mathrm{S} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathrm{G} \\ \mathrm{B} \\ \mathrm{S} \\ \mathrm{R}' \\ \mathrm{G}' \\ \mathrm{B}' \\ \mathrm{S}' \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}. \tag{15}$$

To find the solution of matrix $[\mathrm{R\ G\ B\ S\ R'\ G'\ B'\ S'}]$, it then becomes

$$\begin{bmatrix} \mathrm{G} \\ \mathrm{B} \\ \mathrm{S} \\ \mathrm{R}' \\ \mathrm{G}' \\ \mathrm{B}' \\ \mathrm{S}' \end{bmatrix} = \begin{bmatrix} X_\mathrm{G} & X_\mathrm{B} & X_\mathrm{S} & 0 & 0 & 0 & 0 \\ Y_\mathrm{G} & Y_\mathrm{B} & Y_\mathrm{S} & 0 & 0 & 0 & 0 \\ Z_\mathrm{G} & Z_\mathrm{B} & Z_\mathrm{S} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} X \\ Y \\ Z \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}, \tag{16}$$

and therefore, a set of linear color solution V_1 can be found

$$V_1 = [0\ \mathrm{G\ B\ S\ R'\ G'\ B'\ S'}]. \tag{17}$$

In the same way, if G, B, S, R′, G′, B′, and S′ are set to zero in turn, the other seven sets of basic linear color signals $V_2, V_3, \ldots, V_8$ can be sought out as follows:

$$V_2 = [\mathrm{R}\ 0\ \mathrm{B\ S\ R'\ G'\ B'\ S'}], \tag{18}$$

$$V_3 = [\mathrm{R\ G}\ 0\ \mathrm{S\ R'\ G'\ B'\ S'}], \tag{19}$$

$$V_4 = [\mathrm{R\ G\ B}\ 0\ \mathrm{R'\ G'\ B'\ S'}], \tag{20}$$

$$V_5 = [\mathrm{R\ G\ B\ S}\ 0\ \mathrm{G'\ B'\ S'}], \tag{21}$$

$$V_6 = [\mathrm{R\ G\ B\ S\ R'}\ 0\ \mathrm{B'\ S'}], \tag{22}$$

$$V_7 = [\mathrm{R\ G\ B\ S\ R'\ G'}\ 0\ \mathrm{S'}], \tag{23}$$

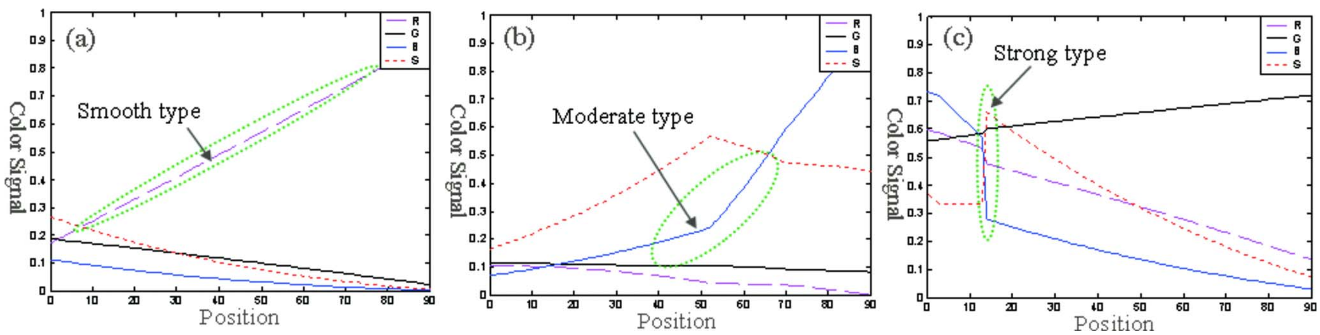


Figure 6. The classifications of four-color signal smoothness.

$$V_8 = [\mathrm{R}\ \ \mathrm{G}\ \ \mathrm{B}\ \ \mathrm{S}\ \ \mathrm{R}'\ \ \mathrm{G}'\ \ \mathrm{B}'\ \ 0]. \qquad (24)$$

Consequently, the linear combination solution $\bar{V}$, which includes eight sets of basic linear color signals $V_1, V_2, \ldots, V_8$ can be established as follows:

$$\bar{V} = \sum_{i=1}^{8} \omega_i V_i, \qquad (25)$$

$$\sum_{i=1}^{8} \omega_i = 1, \quad \omega_i \geq 0. \qquad (26)$$

Finally, only two sets of basic linear color signal solutions called V_i and V_j can be obtained. As a result, all of the feasible linear color signal solutions V_p can be represented by the linear combination of V_i and V_j [see Eqs. (27) and (28)],

$$V_p = pV_i + (1-p)V_j, \quad i = 1-8, \quad j = 1-8, \quad j > i, \qquad (27)$$

$$V_{8\text{-bit}} = \mathrm{round}(255 V_p), \qquad (28)$$

where $V_i = [\mathrm{R}_i,\ \mathrm{S}_i,\ \mathrm{B}_i,\ \mathrm{S}_i]$, $V_j = [\mathrm{R}_j,\ \mathrm{S}_j,\ \mathrm{B}_j,\ \mathrm{S}_j]$, and the coefficient p must be limited in the range of 0–1. The notation of round () means to round to nearest integer; $V_{8\text{-bit}} = [\mathrm{R}_{8\text{-bit}},\ \mathrm{S}_{8\text{-bit}},\ \mathrm{B}_{8\text{-bit}}, \mathrm{S}_{8\text{-bit}}]$ represents the feasible 8-bit color signal solution, and the 4.3 hundred million (i.e., $2^8 \times 2^8 \times 2^8 \times 2^8$) colors will be approximately produced in the four-primary color system. With the same 8-bit color quantizing ability, more color smoothness levels will be displayed in the four-primary color system than in the current three-primary color system, which only produces about 16.4 million colors.

Because the selection of coefficient p in Eq. (27) will affect the tonal smoothness levels on the four-primary color display, it is necessary to find the fitting p value which can achieve the optimal 8-bit color signal $[\mathrm{R}_{8\text{-bit}},\ \mathrm{S}_{8\text{-bit}}, \mathrm{B}_{8\text{-bit}},\ \mathrm{S}_{8\text{-bit}}]$. The tonal smoothness evaluation can be regarded as the objective function for evaluating the four-primary color transformation methods.[10,11] To judge the tonal smoothness levels of four-primary color system, the tonal evaluation curves describing the relation between the color position (variations in lightness, chroma, or hue) and color tonality are classified here. According to the gradients of the tonal evaluation curve, three levels of color signal discontinuity can be classified as: (a) smooth type, (b) moderate type, and (c) strong type (see Figure 6). It can be assumed that the smooth type tonal evaluation curve is the priority to adopt in the four-primary color system because four-primary color images with lower noise will appear on the four-primary color display.

To more precisely evaluate the tonal smoothness levels of four-primary color system, several edge detection methods are applied in each individual color channel of an image. It is desired that the optimal p value in Eq. (27) can be determined according to the tonal smoothness evaluation in experiment 2, below.

Four-Color Channel Separation

To achieve the simulation of four-primary color appearances shown on the Adobe RGB (1998) platform, it is necessary to develop a four-color channel separation algorithm. When a set of feasible linear color signals [R G B S] in the four-primary color system is obtained, four-color channels which are called first channel, second channel, third channel, and fourth channel corresponding to linear color signals [R 0 0 0], [0 G 0 0], [0 0 B 0], and [0 0 0 S] will be separated. To simulate four-color channels on the Adobe RGB (1998) system, the corresponding tristimulus values of [R 0 0 0], [0 G 0 0], [0 0 B 0], and [0 0 0 S] must be converted to new linear RGB color signals within the Adobe RGB (1998) color gamut.

An example describing the first channel of an ideal four-primary color system is given in Eq. (29),

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M \begin{bmatrix} \mathrm{R} \\ 0 \\ 0 \\ 0 \end{bmatrix}, \qquad (29)$$

where M represents the 3×4 matrix defined as in Eq. (6).

On the other hand, the relation between the same tristimulus values and their corresponding linear RGB color signals $[\hat{\mathrm{R}},\ \hat{\mathrm{G}},\ \hat{\mathrm{B}}]$ and can be described in Eq. (30),

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = U \begin{bmatrix} \hat{\mathrm{R}} \\ \hat{\mathrm{G}} \\ \hat{\mathrm{B}} \end{bmatrix}, \qquad (30)$$

where U is the 3×3 matrix defined from the normalized tristimulus values $[X_i, Y_i, Z_i]$ (i=R, G, B) in three-primary color system, and $[\hat{\mathrm{R}},\ \hat{\mathrm{G}},\ \hat{\mathrm{B}}]$ represent the corresponding linear RGB color signals. To approach the colorimetric color reproduction on the Adobe RGB (1998) system, the matrix U is defined according to the sRGB standard.

If Eqs. (29) and (30) are combined, the following Eqs. (31) and (32) will be derived

$$\begin{bmatrix} \hat{\mathrm{R}} \\ \hat{\mathrm{G}} \\ \hat{\mathrm{B}} \end{bmatrix} = \mathrm{inv}(U)M \begin{bmatrix} 0 \\ 0 \\ 0 \\ \mathrm{R} \end{bmatrix}, \qquad (31)$$

$$[\hat{\mathrm{R}}_{8\text{-bit}}, \hat{\mathrm{G}}_{8\text{-bit}}, \hat{\mathrm{B}}_{8\text{-bit}}] = \mathrm{round}(255[\hat{\mathrm{R}}, \hat{\mathrm{G}}, \hat{\mathrm{B}}]). \qquad (32)$$

In the above equations, inv(U) represents the inverse matrix of U, and $[\hat{\mathrm{R}}_{8\text{-bit}}, \hat{\mathrm{G}}_{8\text{-bit}}, \hat{\mathrm{B}}_{8\text{-bit}}]$ represents the 8-bit color signal in the Adobe RGB (1998) system. Therefore, each element of $[\hat{\mathrm{R}}_{8\text{-bit}}, \hat{\mathrm{G}}_{8\text{-bit}}, \hat{\mathrm{B}}_{8\text{-bit}}]$ in an image's pixel on the Adobe RGB (1998) system can be calculated according to Eq. (32). The second, third, and fourth color channels in four-primary color system can be also represented according to the above method.

Edge Detection Methods

Edge detection plays an important role in many image processing applications. The edge represents the discontinuous contour in an image. Three kinds of edge detection methods are tried in the four-primary color system in this article, which are the gradient operation, the Prewitt operation, and the Sobel operation.[12]

Gradient Operation

Gradient operation is a first-order differential calculation to find the variations in color signals in an image. It is the basic concept of edge detection and is described in Eq. (33), where $\nabla f(x,y)$ denotes the gradient of an image $f(x,y)$ at location (x,y)

$$\nabla f(x,y) = \frac{\partial}{\partial x} f(x,y) + \frac{\partial}{\partial y} f(x,y). \qquad (33)$$

Prewitt Operation

Prewitt operation can be regarded as a two-direction spatial filtering operation, which includes the horizontal filter P_x and the vertical filter P_y [see Eqs. (34) and (35)]. Here, the notation $*$ means the spatial convolution calculation. The total gradient $\nabla f(x,y)$ can be written in Eq. (36)

$$P_x(x,y) = \begin{bmatrix} -1 & 0 & 1 \\ -1 & 0 & 1 \\ -1 & 0 & 1 \end{bmatrix} * f(x,y), \qquad (34)$$

$$P_y(x,y) = \begin{bmatrix} -1 & -1 & -1 \\ 0 & 0 & 0 \\ 1 & 1 & 1 \end{bmatrix} * f(x,y), \qquad (35)$$

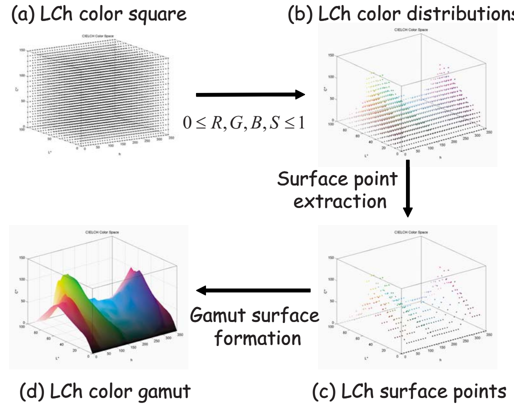


Figure 7. The gamut visualization of 3D *LCh* gamut.

$$\nabla f(x,y) = \sqrt{[P_x(x,y)]^2 + [P_y(x,y)]^2}. \qquad (36)$$

Sobel Operation

Sobel operation is also a two-direction spatial filtering operation, which includes the horizontal filter written in Eq. (37) and the vertical filter written in Eq. (38). The total gradient $\nabla f(x,y)$ also can be defined as same as in Eq. (36);

$$P_x(x,y) = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} * f(x,y), \qquad (37)$$

$$P_y(x,y) = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix} * f(x,y). \qquad (38)$$

Experimental Designs

Three kinds of experiments are implemented in this research. They are "experiment 1: evaluation of 3D *LCh* color gamut," "experiment 2: tonal smoothness evaluation," and "experiment 3: performance of four-color channels."

Experiment 1: Evaluation of 3D LCh Color Gamut

To exactly compare color gamut differences between four-primary color system and three-primary color system, 3D color gamut visualization technology is applied in *LCh* color space.

The concept of 3D *LCh* gamut visualization is shown as Figure 7. First, the *LCh* color boxes filled with equal *LCh* intervals are produced in the ranges of $0 \leqq L^* \leqq 100$, $0 \leqq C^*_{a\mathrm{B}} \leqq 150$, and $0 \leqq h \leqq 360$. Within the [R, G, B, S] limitation range of 0–1, the *LCh* color distributions representing color points covering the four-primary color system can be formed. After the operations of surface point extraction and gamut surface formation, the *LCh* color gamut of a four-primary color system can be obtained. The *LCh* color gamut of three-primary color system is also obtained by a similar operation.

To analyze the cross-display color gamut differences, the 3D color gamuts of the selected four-primary color system

Table II. Designs of test charts.

	Lightness	Hue	Chroma	Test chart
Pattern 1	43	40	0-89	
Pattern 2	75	147	0-80	
Pattern 3	33	306	0-133	
Pattern 4	77	195	0-43	
Pattern 5	48	334	0-89	
Pattern 6	96	102	0-95	
Pattern 7	70	0-360	40	
Pattern 8	70	0-360	14	
Pattern 9	0-100	0	0	

and the Adobe RGB (1998) system are drawn in *LCh* color space simultaneously. Meanwhile, the gamut coverage ratio (GC ratio) on h-L^* color plane can be calculated as follows:

$$\text{GC ratio} = N_{\text{in-gamut}}/N_{\text{total}}, \tag{39}$$

where $N_{\text{in-gamut}}$ represents the sample numbers of test color gamut (i.e., four-primary color system or sRGB system) inside the Adobe RGB (1998) system, which are projected on the h-L^* color plane; N_{total} represents total sample numbers in the Adobe RGB (1998) system projected onto the h-L^* color plane. In this case, N_{total} is defined as $360\times 99=35{,}640$ (i.e., hue sample ranking 0, 1,…,359, and lightness sample ranking 1,2,…,99).

The GC ratio can be used as a gumut coverage guideline to show that the Adobe RGB (1998) system covers the test color systems. Our test color systems include one kind of three-primary color system (i.e., sRGB) and three kinds of four-primary color systems (i.e., sRGB+K60, sRGB+K56, and sRGB+K80).

Experiment 2: Tonal Smoothness Evaluation

In this article, a series of test color charts is designed to evaluate four-primary color tonal smoothness. They include [C], [M], [Y,] [R], [G], [B] color tones (for testing chroma change), neutral color (for testing lightness change), and two hue circles (for testing hue changes; one with lower chroma and the other with higher chroma). A total of 11 individual test charts is designed to evaluate the tonal smoothness of four-primary color system (see Table II).

For a known color stimulus corresponding to a given patch, the L3C program is applied to find the optimal four-primary color signals. When the coefficient p in Eq. (27) is assigned within the range of 0 and 1, the relationship of two sets of basic four-color linear signals, V_i and V_j, can be established. The p value is set to 1/6, 6/2, 3/6, 4/6, and 5/6 in turn and is tested to find which V_p value in Eq. (27) has a capacity of achieving smoother color tones in all test color charts.

Figure 8 shows an example of tonal evaluation curves for testing the achromatic color chart (i.e., "pattern 9"). It is observed that when the p value is near to 1/2 (e.g., $p=3/6$), all four-primary linear color signals [R G B S] converge to

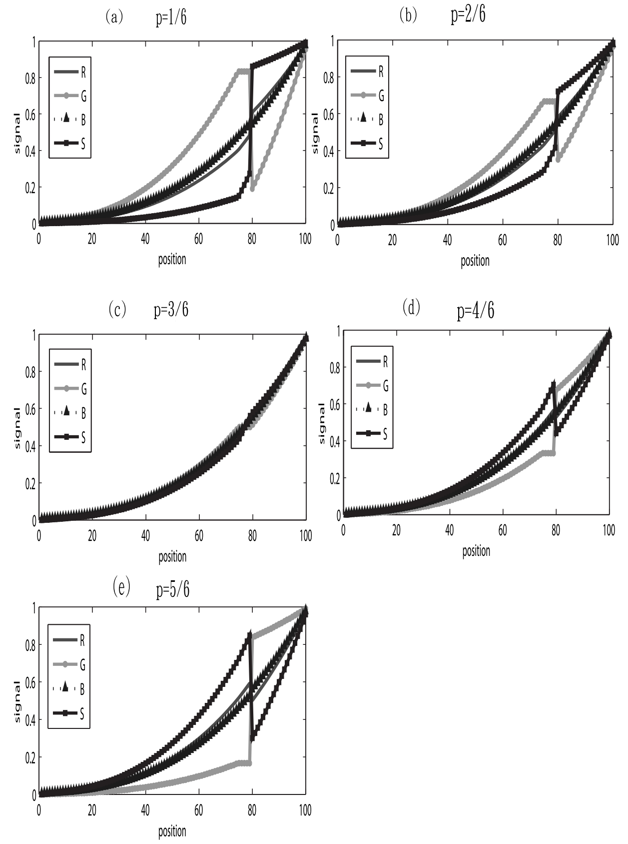


Figure 8. The tonal evaluation curves of achromatic color in four-primary color system (pattern 9).

smooth types simultaneously. To more precisely evaluate the tonal smoothness levels of the four-primary color system, the Prewitt and Sobel operations are applied to each of the four-color channels. If the tonal discontinuity occurred in the assigned color channel, it should be easily detected by the above effective edge detection methods. It is desired that the optimal p value be determined according to the evaluation result in experiment 2.

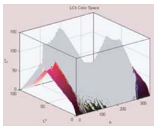
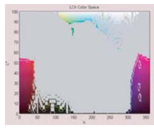
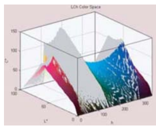
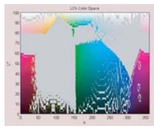
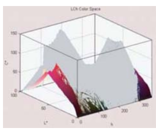
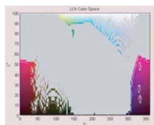
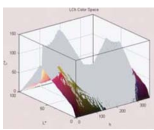
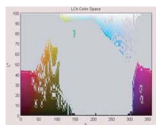
Experiment 3: Performance of Four-Color Channels

For a color image displayed on a four-primary color system, its corresponding linear RGB signals $[\hat{R},\hat{G},\hat{B}]$ in the sRGB system can be obtained by Eq. (31). Then $[\hat{R}_{8\text{-bit}}, \hat{G}_{8\text{-bit}}, \hat{B}_{8\text{-bit}}]$ values of a pixel corresponding to the four-color channels in a four-primary color system can be easily simulated on the Adobe RGB (1998) monitor.

To check the performance of the proposed color conversion method, we select one test chart "pattern 7" and one test image "wool" to demonstrate their four-color channels on the calibrated EIZO ColorEdge 221 LCD monitor. The γ curves, color temperate and [R], [G], [B] chromaticity coordinates of this monitor are calibrated as near to the Adobe RGB (1998) standard as possible with the $\gamma=2.2$ tone reproduction curve.

Therefore, the four-primary color system which has the maximum GC ratio from experiment 1 will be picked to simulate four-color channels of the selected test chart or test image on the Adobe RGB (1998) monitor.

Table III. Comparisons of *LCh* color gamuts

No.	Item / Name	LCh color space	h-L plane	GC ratio
1	Adobe RGB v.s. sRGB			97.2 %
2	Adobe RGB v.s. sRGB+K60			72.4 %
3	Adobe RGB v.s. sRGB+K56			96.1 %
4	Adobe RGB v.s. sRGB+K8			96.0 %

Experimental Results

Three kinds of experimental results are arranged as follows:

Experiment 1: Evaluation of 3D LCh Color Gamut

Table III demonstrates the simulation results in experiment 1: the 3D *LCh* color gamut comparisons between the Adobe RGB (1998) monitor and four kinds of test color systems, including (1) the Adobe RGB (1998) versus sRGB, (2) the Adobe RGB (1998) versus sRGB+K60, (3) the Adobe RGB (1998) versus sRGB+K56, and (4) the Adobe RGB (1998) versus sRGB+K8.

In the figures of *LCh* color space and *h-L* plane from Table II, the full color surface represents the Adobe RGB (1998) system and the gray color surface represents the color system being tested. The calculated GC ratios show that the sets of No. 3 and No. 4 have higher gamut coverage ratios (96.1%, 96.0%) than others. It hints that the Adobe RGB (1998) system can simulate color appearances of sRGB, sRGB+K56 and sRGB+K8 color systems but cannot simulate sRGB+K60 due to its insufficient GC ratio (72.4%). Therefore, the Adobe RGB (1998) platform has the ability to simulate four-primary color appearance when the four-primary color systems correspond to sRGB+K56 or sRGB+K8.

Experiment 2: Tonal Smoothness Evaluation

Figures 9 and 10 demonstrate the color separation results of all test patterns in the sRGB+K8 and sRGB+K56 system using different *p* values. The horizontal direction represents the *p* value (i.e., 1/6, 6/2, 3/6, 4/6, and 5/6) and the vertical direction represents the color channel appearance {i.e., first channel [R], second channel [G], third channel [B], and fourth channel [S]}.

The edge detection results by Prewitt operation applied to all test patterns in the four-primary color systems of sRGB+K8 and sRGB+K56 are shown in Figures 11 and 12, respectively. It is clear that the locations with tonal discontinuity in the four-color channels in Figs. 8 and 9 can be detected by the Prewitt operation because Prewitt filtering has the capacity of detecting vertical edges in an image. The detection results indicate that better tonal smoothness in each four-color channel of sRGB+K8 and sRGB+K56 sys-

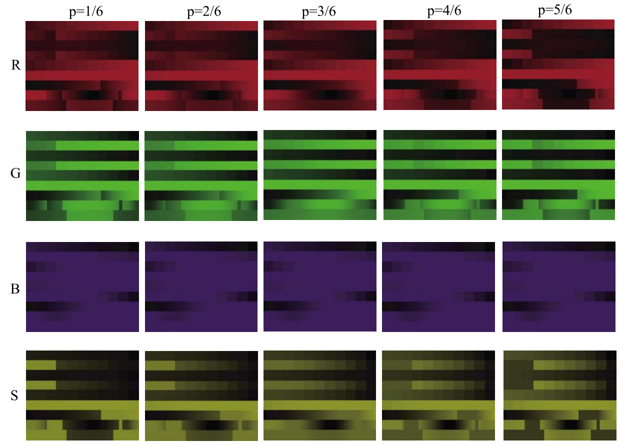


Figure 9. Four-color channels in the sRGB+K8 system using different *p* settings (all test patterns).

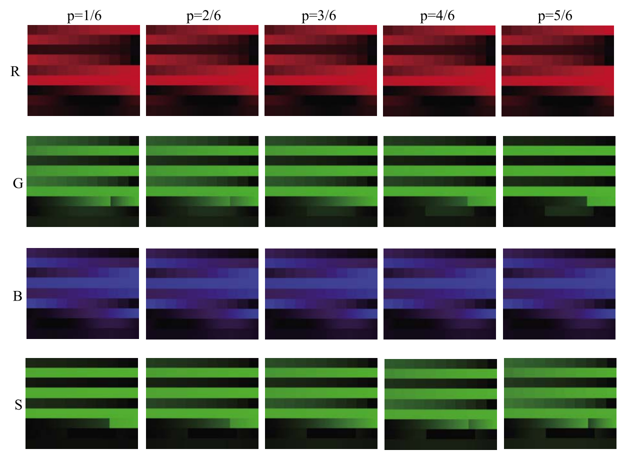


Figure 10. Four-color channels in the sRGB+K56 system using difference *p* settings (all test patterns).

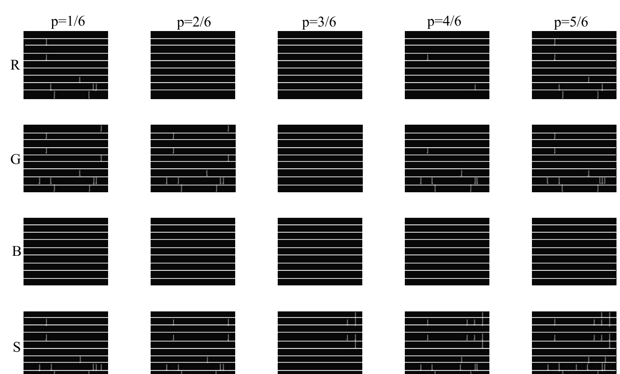


Figure 11. Tonal smoothness evaluations in the sRGB+K8 system using Prewitt operation (all test patterns).

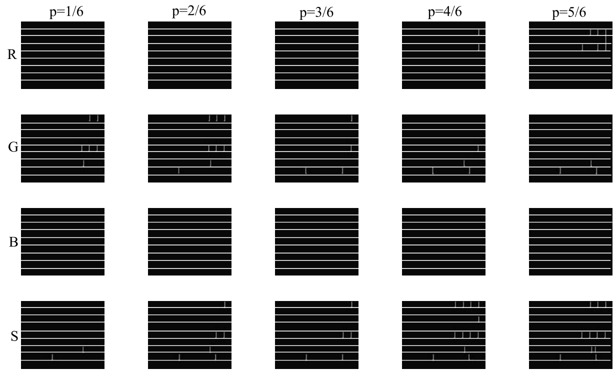


Figure 12. Tonal smoothness evaluations in the sRGB+K56 system using Prewitt operation (all test patterns).

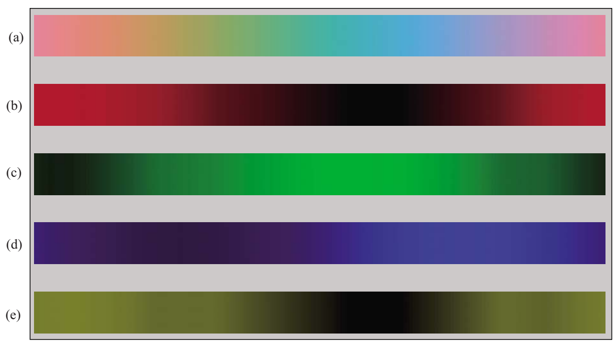


Figure 13. Four-color channels of simulating the sRGB+K8 system: (a) original color chart, (b) first channel, (c) second channel, (d) third channel, and (e) fourth channel (pattern 8).

tems can be achieved when the *p* value is set near one-half. These detected vertical lines in Figs. 10 and 11 approximately match the discontinuities directly observed by the human eye. In addition, the edge detection results of the Sobel operation are also close to those of the Prewitt operation. It is obvious that either the Prewitt or Sobel operations can be applied to vertical edge detection in an four-primary color image.

Experiment 3: Performance of Four-Color Channels

Figure 13 demonstrates an example of four-color channels of the hue-circle chart (i.e., pattern 7) when the four-primary color system is set to sRGB+K8. The sub-figures in Fig. 13 are: (a) original color chart, (b) first channel [R], (c) second channel [G], (d) third channel [B], and (e) fourth channel [S]. The color separation results show that the smoother color gradations can be achieved on each color channel using the proposed color separation method.

An example of traditional three-color channel reproduction of the test image "wool" is given in Figure 14. Its four-color separation results with different fourth color settings in experiment 2 are also shown in Figure 15. The subfigures: (a) correspond to the sRGB+K8 color system and (b) correspond to the sRGB+K56 color system. The color pictures in Fig. 15 show that the third channels [B] in subfigures (a) and (b) have similar contrast and blue color appearance, while the fourth channels [S] have obviously different image appearances.

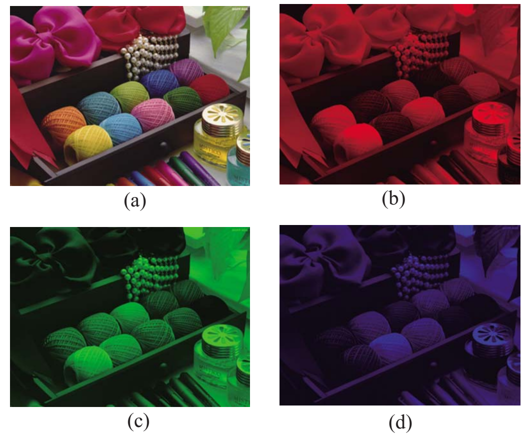


Figure 14. Test image wool and its traditional three-color channels: (a) original image, (b) red channel, (c) green channel, and (d) blue channel.

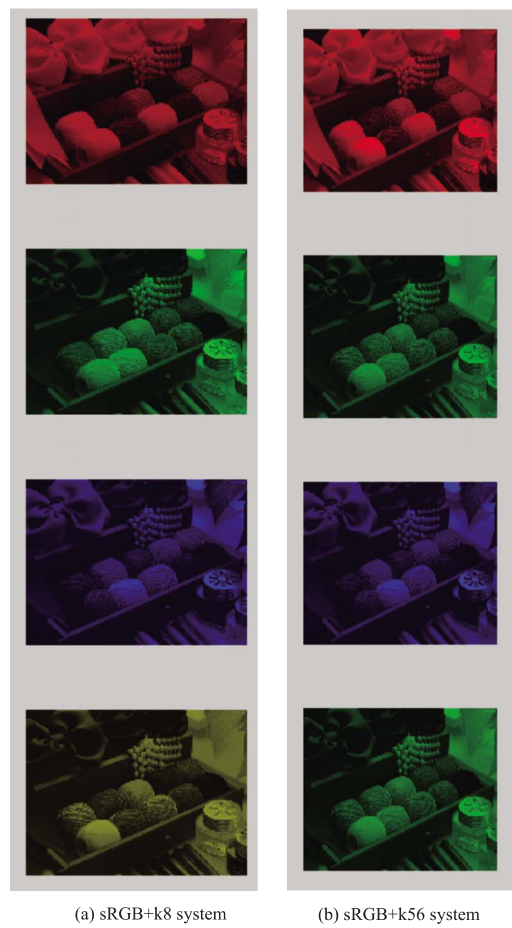


Figure 15. The color separation channels of test image wool in four-primary color systems; (a) sRGB+K8 system and (b) sRGB+K56 system.

Although the same three-primary chromaticity coordinates {i.e., [R], [G], [B] colors of sRGB standard} are selected in the sRGB+K56 and sRGB+K8 color systems, the different choices of the fourth colors cause dissimilar color separation channels. We can observe that the fourth color channels in two kinds of four-primary color systems are obviously different insofar as they mainly comprise the color components of K8 (yellow) and K56 (green), respectively.

Also, notice that the sRGB+K8 system includes red color (first channel), green color (second channel), blue color (third channel), and yellow color (fourth channel); while the sRGB+K56 system shows an image having red color (first channel), green color (second channel), blue color (third channel), and bright-green color (fourth channel).

CONCLUSIONS

A new four-primary color conversion model based on linear programming to formulate the convex optimization problem, named linear color convex combination, is proposed. It is easily applied to a wide color gamut RGB monitor to simulate four-primary color channels of a color image. Meanwhile, the optimal four-color signals can be determined according to the tonal smoothness evaluation based on edge detection by Prewitt or Sobel operations.

The color channel separation and color channel simulation of four-primary color system have also been developed for the Adobe RGB (1998) system. The gamut coverage ratio can be regarded as an objective metric for the development of the four-primary color system on the Adobe RGB (1998) system. These color simulation technologies will benefit color system design for four-primary color displays.

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