Color conversion technology of 4-primary color images developing on wide color gamut RGB monitor

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Abstract

To assist with the colorimetric design of 4-primary color display, it is necessary to build up 4-primary color simulation platform on wide color gamut RGB monitor.

A new 4-primary color conversion algorithm that can simulate 4-primary color image appearance built on wide color gamut RGB monitor is proposed.

The experimented 4-primary colors are composed of red, green, blue colors based on sRGB standard and the addition of the 4^{th} primary color. The 4^{th} primary colors are selected from Kodak Wratten color filters which CIE u'v' colorimetric coordinates are located in the range between sRGB triangle gamut and Adobe RGB triangle gamut. The 4-primary color conversion is implemented on Adobe RGB platform to simulate 4-primary color gamut.

The Convex Hull is introduced to establish color conversion between 4-primary color signal and the corresponding color stimulus. Finally, 4-primary color conversion is also applied to build up 4-color separation channels, which can simulate 4-color separation images shown on Adobe RGB platform. It is demonstrated that color conversion algorithm based on Convex Hull well performs on 4 color separation channels on Adobe RGB platform.

Introduction

The development of WCG (wide color gamut) display plays an important role in the high-quality TV field in the future. Multi-primary color LCD with more primary color filters (≥3) is one of useful technologies to approach to WCG display. In the current display system, all of the color images are recorded and transformed by RGB 3-primary formatted. To build up 4-primary color system, it is necessary to develop color conversion model between 3-primary color system and 4-primary color system.

Several important color conversion algorithms for designing multi-primary color display system are arranged here. Ajito et. al. (2001) developed the matrix switching method [1]. It splits the color gamut of multi-primary display into pyramid 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. H. Motomura et. al. (2003) proposed the method called LIQUID based on linear interpolation on equi-luminance plane [2]. It performs linear interpolation value on luminance and saturation axes continuity. This method has smoother tones than matrix switching method when hue is switched. F. König et. al. (2002) proposed Metameric black method. This method shows smoother tones than the methods of LIQUID and matrix switching when color gradations are switched [3]. Meanwhile, Dan Eliav et. al. (2006) introduced the guideline for choosing color filters of 4-primary configuration. They suggested that the addition of yellow can enhance the luminance and allow flexibility in the chromaticity of the green primary [4].

In this paper, a new 4-primary color conversion model based on Convex Hull is proposed. It is easily designed in wide color gamut RGB monitor to simulate 4-primary color channels of color image.

Build up 4-primary color system

Figure 1 demonstrates that color conversion flow from 3-primary color system to 4-primary color system. Firstly, all pixels of input 3-primary color image are converted to the corresponding color stimulus values according to sRGB standard. The tristimulus values of each pixel will be separated into 4 color signals by using proposed color conversion algorithm, then 4 color separation channels will be created on Adobe RGB monitor.

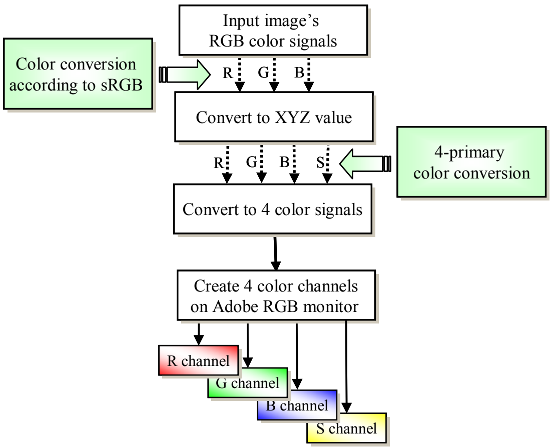


Figure 1. Color conversion of 3-primary colors and 4-primary colors

Adobe RGB monitor is utilized to simulate 4 color channels in our research. Meanwhile, the designed 4-primary color system is composed of red, green, blue colors ([R], [G] and [B]) and the addition of 4^{th} primary color [S]. The colorimetric coordinates of 3-primary colors [R], [G] and [B] are designed as same as sRGB standard, while the 4^{th} primaries [S] are selected from the spectral transmission database of 12 Kodak Wratten color filters (i.e. K8, K15, K22, K31, K32, K33, K34a, K44, K45, K56, K60 and K64. Here, prefix "K" means Kodak Wratten color filter) [5]. The spectral transmission curves (400~700 nm) of test color filters are shown as **Figure 2**. Under the condition of D_{65} illuminant and 2 degree XYZ color matching functions, their u'v' chromatic values are calculated (see **Figure 3**).

To achieve to simulate 4-color image appearance on Adobe RGB platform further, the 4^{th} primaries [S] are selected from Kodak Wratten color filters, which colorimetric values are located between sRGB color gamut and Adobe RGB color gamut. As a result, K60, K56 and K8 can be satisfied with the above u'v' gamut limitation. Because the colormetric combinations based on CIE u'v' diagram are lack of lightness information, it is difficult to judge which filter is out-of-gamut or in-gamut exactly. Therefore, it is necessary to further analyze the selected color filters in 3-D LCh color space.

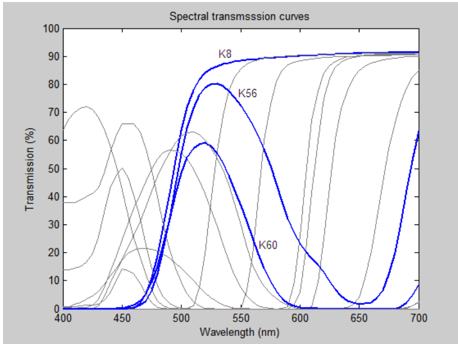


Figure 2. Spectral transmission curves of test Kodak Wratten filters

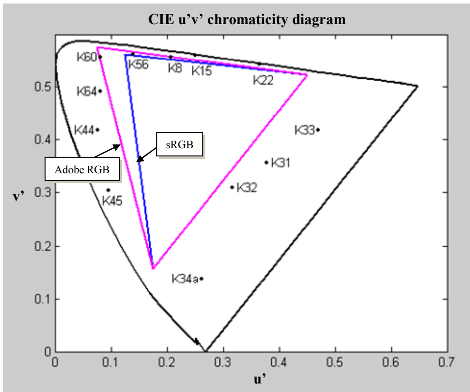


Figure 3. Colorimetric coordinates of test Kodak Wratten filters

Design of color conversion algorithm

The proposed 4 color conversion algorithm is to deal with color conversion between 3-color system and 4-color system. In 4-color system, there is the relation of **Equations 1&2** between color signal amounts and its color tristimulus values basically. In this paper, the white luminance in 4-primary color platform is set to 80 cd/m^2 in order to match sRGB standard.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M \begin{bmatrix} R \\ G \\ B \\ S \end{bmatrix} \quad ; 0 \leqq R, G, B, S \leqq 1 \qquad (1)$$

$$M = \begin{bmatrix} X_R & X_G & X_B & X_S \\ Y_R & Y_G & Y_B & Y_S \\ Z_R & Z_G & Z_B & Z_S \end{bmatrix} \qquad (2)$$

Where [R,G,B,S] represents the linear color signal amount of 4 primary colors. Each element of [R,G,B,S] is limited within the range of 0~1. [X,Y,Z] is the normalized tri-stimulus value of mixture color and M is the 3-by-4 matrix consisited of the normalized primary tristimulus values $[X_i\ Y_i\ Z_i]^T$ (*i=R,G,B,S*). Because the matrix M is not a symmetrical form, the Convex Hull is used to find the optimal signal solution [6].

Basically, the above 4-color signal solution optimization can be regarded as the equivalent convex problems. Four new variables [*R',G',B',S'*] and equality constraints can be introduced into the color conversion algorithm based on the concept of Convex Hull (see **Equations 3~6**).

R+R'=1 , 1≧R'≧0 (3)

G+G'=1 , 1≧G'≧0 (4)

B+B'=1 , 1≧B'≧0 (5)

S+S'=1 , 1≧S'≧0 (6)

Furthermore, the new condition between 8 variables [*R,G,B,S, R',G',B',S'*] and tristimulus values XYZ can be established as **Equations 7 & 8**, where N is 7x8 matrix.

$$[X \quad Y \quad Z \quad 1 \quad 1 \quad 1 \quad 1]^T = N[R \quad G \quad B \quad S \quad R' \quad G' \quad B' \quad S']^T \qquad (7)$$

$$N = \begin{bmatrix} X_R & X_G & X_B & X_S & 0 & 0 & 0 & 0 \\ Y_R & Y_G & Y_B & Y_S & 0 & 0 & 0 & 0 \\ Z_R & Z_G & Z_B & Z_S & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (8)$$

It becomes a problem of seeking for the feasible [*R,G,B,S,R',G',B',S'*] solutions in Equation 7. If each elements of [*R,G,B,S,R',G',B',S'*] is set to zero in terns, only two sets of basic solutions called K_1 & K_2 can be obtained finally. As a result, all of the feasible solution K_p in Equation 7 can be represented as follows:

$$K_p = pK_i + (1-p)K_j \qquad (9)$$
$$i=1\sim 8,\ j=1\sim 8;\ i \neq j$$

Where *p* represents an arbitrary value between 0 and 1. Because the setting of *p* will affect the smoothness level of color graduation shown on the display, it is necessary to find the *p* value which can achieve the optimal feasible solution [*R,G,B,S*]. In our previous research, when *p* is set near to 1/2, the better smoothness of displayed color graduation can be achieved [7]. Finally, for any color stimulus of input image pixel, the optimal [*R,G,B,S*] solution will be sought.

4-color separation

4-color separation is attempted to perform on Adobe RGB platform. For a set of feasible [*R,G,B,S*] color signals in 4-color system, it can be separated into 4-color channels respectively. They are 1st channel, 2nd channel, 3rd channel and 4th channel which are corresponding to image appearances of [*R,0,0,0*], [*0,G,0,0*], [*0,0,B,0*] and [*0,0,0,S*]. To simulate 4-color channels on Adobe RGB platform, the corresponding tristimuls values of [*R,0,0,0*], [*0,G,0,0*], [*0,0,B,0*] and [*0,0,0,S*] must be converted to new RGB color signals.

Give an example of 1st channel of 4-color system, it can be described as **Equation 10**.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M \begin{bmatrix} R \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad (10)$$

Where M is the 3-by-4 matrix defined as same as Equation 2.

On the other hand, the relation between RGB color signal amounts and its corresponding tristimulus values can be described as Equation 11.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = N \begin{bmatrix} \hat{R} \\ \hat{G} \\ \hat{B} \end{bmatrix} \qquad (11)$$

Where N is the 3-by-3 matrix defined from the normalized primary tristimulus values $[X_i, Y_i, Z_i]$ (i=R,G,B) in 3-color RGB system, and $[\hat{R}\ \hat{G}\ \hat{B}]$ represents 3-color linear RGB signal amount. To achieve colorimetric color reproduction on Adobe RGB platform, the matrix T is defined from sRGB standard.

When Equation 10 and Equation 11 are combined together, the following **Equation 12** will be derived.

$$\begin{bmatrix} \hat{R} \\ \hat{G} \\ \hat{B} \end{bmatrix} = N^{-} M \begin{bmatrix} R \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad (12)$$

In the above equation, N^{-} represents inverse matrix of N. Then $[\hat{R}, \hat{G}, \hat{B}]$ amount of image pixel on Adobe RGB platform can be calculated by Equation 12.

The 2nd, 3rd, 4th channels in 4-color system can be also represented by the above method.

Experiment

Two experiments are implemented in our research. They are "Evaluation of 3-D LCh color gamut (Exp1)" and "Performance of 4-color separation channels (Exp2)".

- Exp 1: Evaluation of 3-D LCh color gamut

To compare color gamut differences between 4-color system and 3-color system, 3-D color gamut visualization is built up in LCh color space.

The concept of 3-D LCh gamut formation is shown as **Figure 4**. Firstly, the LCh color square with equal LCh intervals are produced in the ranges of $0 \leqq L^* \leqq 100$, $0 \leqq C_{ab}^* \leqq 150$ & $0 \leqq h \leqq 360$. With the 0~1 limitation of the $[R, G, B, S]$, LCh color distributions representing color points in the 4-color gamut can be formed. Furthermore, after the operations of "surface point extraction" and "gamut surface formation", LCh color gamut of 4-color system can be obtained.

The LCh color gamut of 3-color system is also adopted the similar operation.

For analyzing color gamut differences, the color gamuts of the experimented 4-color system and Adobe RGB monitor are drawn in the same LCh color space. Meanwhile, the gamut coverage ratio (GC ratio) on h-L^* color plane is calculated as follows:

$$GC\ ratio = N_{out\text{-}of\text{-}gamut} / N_{total} \qquad (13)$$

Where $N_{out\text{-}of\text{-}gamut}$ represents the color sample numbers of Adobe RGB platform outsides test color gamut (i.e. 4-primary colors or sRGB colors) on h-L^* color plane, and N_{total} represents total color sample numbers of Adobe RGB platform on h-L^* color plane. In this case, N_{total} is defined as 360 * 99= 35640 (i.e. hue sample numbers 0,1…359 and lightness sample numbers 1,2…99).

The GC ratio can be use to evaluate color gamut area ratio which Adobe RGB platform covers the test color system gamut. Our test color systems include 1 kind of 3-color system (i.e. sRGB) and 3 kinds of 4-color system (i.e. sRGB+K60, sRGB+K56 and sRGB+K80). The GC ratio is designed within 0~1. It can be regarded as the color reproduction abilities of Adobe RGB platform reproducing other test color systems.

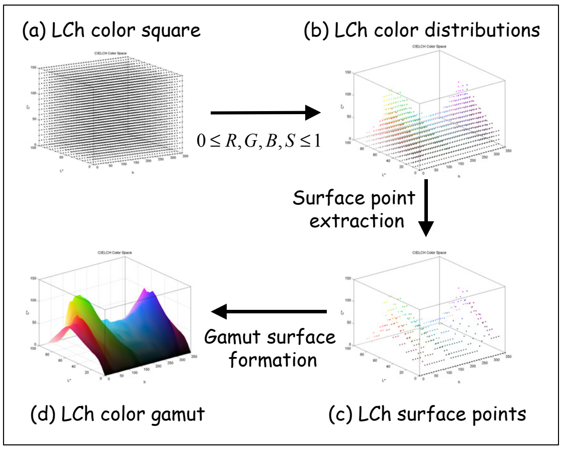


Figure 4. The formation of 3-D LCh gamut

■ <u>Exp 2: Performance of 4-color separation channels</u>

For a color image on 4-color platform, its linear RGB signals of color channel can be obtained by Equation 12. Then $[\hat{R},\hat{G},\hat{B}]$ values corresponding to the color channels in 4-color system can be input to Adobe RGB monitor for the 4-color channels demo.

To check the performance of the proposed color separation method, we select a test chart (hue circle with high chroma) and a test image ("wool") to demo their color channels on the EIZO ColorEdge 221 LCD monitor. The γ curves, color temperate and [R],[G],[B] chromaticity coordinates of this monitor are calibrated as near as Adobe RGB standard.

Results

Table 1 demonstrates Exp 1 performance results: LCh color gamut comparisons between Adobe RGB monitor and 4 kinds of test color systems, including (1) Adobe RGB v.s. sRGB, (2) Adobe RGB v.s. sRGB+K60, (3) Adobe RGB v.s. sRGB+K56 and (4) Adobe RGB v.s. sRGB+K8.

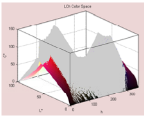
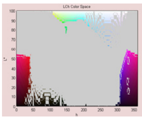
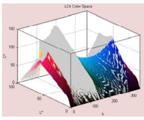
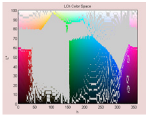
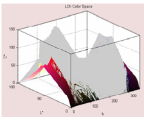
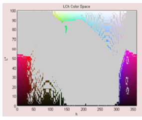
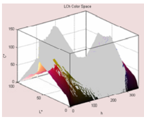
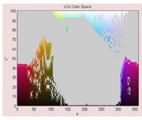
In the figures of LCh color space and h-L plane at Table 1, full color surface represents Adobe RGB platform and gray color surface represents assigning test color system. The calculated GC ratios show No.(3) & (4) have higher scores (96.1 %, 96.0 %). It hints that Adobe RGB platform well fit to simulate image appearances of sRGB, sRGB+K56 and sRGB+K8; but doesn't fit to simulate sRGB+K60 colors due to its lower GC value (72.4%). Therefore, Adobe RGB platform have ability to simulate 4-primary color image appearance when the 4-color systems is sRGB+K56 or sRGB+K8 color.

Figure 5 demonstrates an example of 4-color channels of hue-circle chart when the 4-color system is sRGB+K8 color. The sub-figures of (a),(b),(c),(d) are original hue-circle color chart, (b) 1st channel [R], (c) 2nd channel [S], (d) 3rd channel [B] and (e) 4th channel [S]. The color separation results show that the smoother color gradations are achieved on each color channel.

An example of traditional 3-color separation channel for the test image "wool" is shown as **Figure 6**. Its 4-color separation results with different 4th color settings in Exp.2 are shown at **Figure 7**. The sub-figure (a) is set to sRGB+K8 colors and the sub-figure (b) is set to sRGB+K56 colors. The results show that the 3rd channels [B] in sub-figures (a) and (b) have similar contrast and blue color, while their 4th channels [S] have obviously different image appearances.

Although There are the same 3-primaty color chromaticity coordinates (i.e. [R],[G],[B] colors of sRGB standard) in sRGB+K56 and sRGB+K8 color systems, the different additions of the 4th colors will cause dissimilar color separation channels. We can observe that the 4th color channels in two 4-color systems are obviously different because they are produced from K8 (yellow color) and K56 (green color) colors respectively. Also, notice that sRGB+K8 system includes red color (1st channel), green color (2nd channel), blue color (3rd channel) and yellow color (4th channel); while sRGB+K56 system show red color (1st channel), green color (2nd channel), blue color (3rd channel) and bright-green color (4th channel).

Table 1.　LCh color gamut comparisons

No.	Name \ Item	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 %

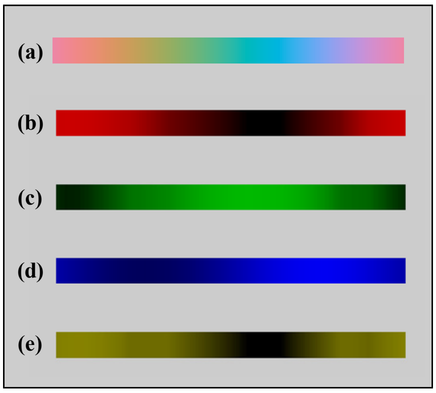


Figure 5.　Four color channels for simulating sRGB+K8 system: (a) original color chart, (b) 1st channel, (c) 2nd channel, (d) 3rd channel and (e) 4th channel

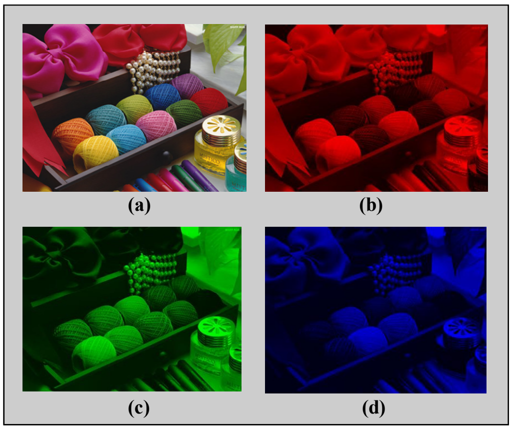
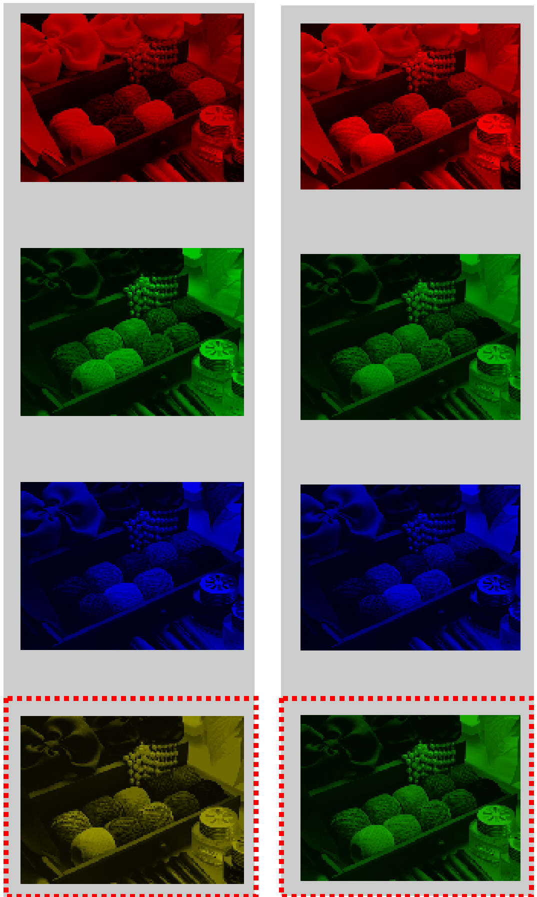


Figure 6.　Test image "wool" and 3 color channels. (b) red channel, (c) green channel, (d) blue channel

Conclusion

Convex Hull has been introduced to build up color conversion algorithm in 4-primary color system successfully. The color separation model and color channel simulation method for 4-primary color system are also built up on Adobe RGB platform.

The gamut coverage (GC) ratio can be regarded as a guideline of developing the 4-primary color system built on Adobe RGB platform. These color technologies will benefit to the colorimetric design of new 4-primary color display system.



(a) sRGB+K8　　*(b) sRGB+K56*

Figure 7.　Color separation channels of color image: (a) sRGB+K8 and (b) sRGB+K56

Acknowledgements

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Reference

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