Extended colour space for capturing devices

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ABSTRACT

DSCs (Digital Still Cameras) have become one of the most popular device among digital color imaging devices. The accuracy of colour reproduction of DSCs has improved with an optimization of colour filter spectral sensitivity design and image processing pipeline. To store these accurate colours throughout wide-range of colour gamut, wide-gamut colour space is necessary. Some of proposed wide-gamut colour spaces are compared in various aspects.

1. INTRODUCTION

With the widespread of DSCs, the demand for the image quality, especially for the color reproduction accuracy is highly increasing. Color reproduction performance is dependent on the shapes of CCD color filters' spectral sensitivity curves. The spectral sensitivity also affects noise performance, as it changes efficiency of light transmittance. Generally speaking, color reproduction characteristics and noise characteristics are in trade-off relationship. Therefore, the evaluation method is indispensable that can evaluate both color characteristics and noise characteristics at the same time. We propose the evaluation method of CCD color filter spectral sensitivities by two dimensional visualization of a trade-off relationship between color and noise performance.

In addition, DSC-captured images need to be stored in unambiguously defined standard color space so that output device can accurately reproduce those images. By using sYCC color space which has much larger color gamut than sRGB, highly-saturated colors can be stored accurately that are outside of sRGB-gamut. Recently, there are several other extended-gamut color spaces proposed. In this paper, these color spaces are compared in the aspect of media-gamut coverage ratio and quantization interval. Also, xvYCC color space is evaluated, which is newly proposed at IEC. xvYCC color space extends video image's color gamut without losing compatibility to current video coding.

2. SPECTRAL SENSITIVITY FOR CAPTURING DEVICES

2.1. Metric for spectral sensitivity evaluation

There has been many metrics proposed for evaluating spectral sensitivity of capturing devices. Table 1 lists some of those representative metrics[1-4].

Table 1. Comparison of representative metric for spectral sensitivity evaluation

Metric	# of Filters	Reflectance of Real Objects	Consideration of Noise
q-factor	1	No	No
μ-factor	plural	No	No
FOM	plural	Yes	Yes (floor noise only)
UMG	plural	Yes	Yes

For metrics like q-factor[1] and μ-factor[2], the basic idea is to calculate the approximation accuracy from the color matching function to the spectral sensitivity of color filter sets, or vice versa. The metric becomes "1" if the Luther condition is fully satisfied, and the value decreases if the spectral sensitivity deviates from the Luther condition. Although it is regarded that color reproduction is more accurate if the metric is closer to "1", it should be noted that this is only a sufficient condition and not a necessary condition for accurate color reproduction. It is known that there are many filter sets that produces accurate colors with those metric not being closer to "1"[5]. Therefore, some of the advanced metrics like FOM[3] (Figure of Merit) and UMG[4] (Universal Measure of Goodness) takes into account of the spectral sensitivity of real object reflectance in their metric calculations.

However, for most of these proposed metrics, noise characteristics are not considered properly, which is one of the fundamental factor in the image quality of DSC-captured images. In the FOM and UMG metrics, noise are taken into account (in FOM, only the floor noise is considered), but since they treat color characteristics and noise characteristics at the same time (or one-dimensionally), it is difficult to evaluate these two characteristics separately (or two-dimensionally). Therefore, in this paper, we propose two dimensional evaluation of color filter spectral sensitivity, by which one can evaluate color filter sets intuitively.

2.2. Two-dimensional evaluation of color filter sets

In this section, two-dimensional evaluation method for the spectral sensitivity of the color filter sets is briefly described. First, color metric is calculated as follows. Color difference in CIELAB space between reproduced image and original scene is calculated using 24 colors of GretagMacbeth ColorChecker[6]. Since CCD signals are converted by matrix operation to produce "standard" RGB space (note: in this calculation, over-ranged RGB values are not clipped), the metric will be dependent on the matrix coefficients.

$$\overline{\Delta E}(MAT) = \frac{1}{24}\sum_{k=1}^{24}\Delta E_k(MAT)$$
$$\Delta E_k(MAT) = \sqrt{\left(\Delta L^*\right)^2 + \left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2}$$

It is known that amount of noise variance: σ at CCD can physically be simulated[7-9]. When these CCD signal goes through DSC's imaging pipeline, noise will be propagated through image processing calculations. We used noise propagation theory[10] to calculate the amount of noise variance in CIELAB space that will be perceived by human visual system. Noise metric: sTN is defined as follows. It should be noted that weighting factors were introduced for σ_{a*} and σ_{b*} in the noise metric by our internal experiments, since noise perception is different for luminance component and chroma component. As in color metric, average sTN value of 24 color patches was calculated.

$$\overline{sTN}(MAT) = \frac{1}{24}\sum_{k=1}^{24} sTN_k(MAT)$$
$$sTN = \sqrt{\left(\sigma_{L*}\right)^2 + \left(\frac{\sigma_{a*}}{w_{a*}}\right)^2 + \left(\frac{\sigma_{b*}}{w_{b*}}\right)^2}$$

As mentioned above, color metric and noise metric are dependent on matrix coefficients in image processing pipeline. First, CEM (Comprehensive Error Metrc) is defined as follows, using aforementioned two metrics.

$$CEM(MAT) = \sqrt{(wc \cdot \overline{\Delta E}(MAT))^2 + (wn \cdot \overline{sTN}(MAT))^2}$$
$$where \quad wc + wn = 1$$

"wc" and "wn" in the above equation are weighting factors for color and noise, respectively. After fixing these weights, the matrix coefficients are calculated as to make CEM value minimum.

Consequently, color metric and noise metric can be calculated at the given weighting factors. Next, after changing the weighting factors, same procedure is operated for the new sets of weighting factors. Finally, calculated color and noise metric are plotted for various weights at two-dimensional figure of color vs. noise (it is named CN plot, here). We can then observe the trade-off relationship between color and noise performance. If the plot is located left-bottom (ie closer to the origin), the filter characteristic is regarded better.

In the Figure 1, conventional primary-color (RGB) filter, conventional complimentary-color (CMYG) filter and newly-developed four-color (RGB+E) filter are compared. Four color super-HAD CCD was implemented in our product called DSC-F828[11-12] in 2003, in which Emerald filter was introduced in addition to conventional RGB color filters. As easily seen from the figure, complimentary color filters are located upper right and it is understood that they are not in good performance in noise characteristics. Similar results can be found in Barnhofer et al's paper[13]. In these CMYG filters, propagated chroma noise becomes larger than primary color filters. 4-color filter performs slightly better than conventional 3-color RGB filter, and color difference was almost halved at the noise level of 1.2.

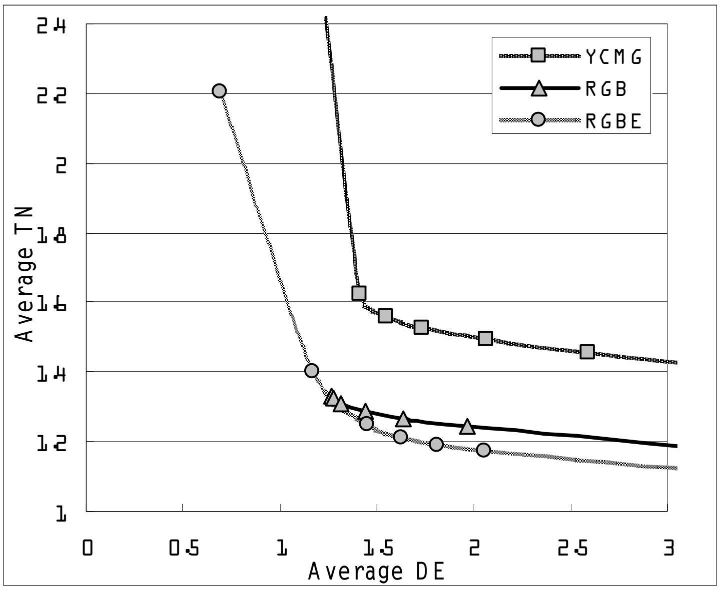

Figure 1. CN Plot: relationship between color and noise performance of several color filter sets (primary RGB filter, complimentary CMYG filter, and newly-developed RGB+E filter)

3. EXTENDED-GAMUT COLOR SPACES

Even though colors are captured and stored faithfully by DSCs as mentioned above, it is also important those colors are accurately transmitted and reproduced by output devices. Therefore, it is necessary to use unambiguously defined standard color space to exchange those images. In our DSCs, sYCC color space is used to store those saturated colors. sYCC color space was standardized internationally as IEC61966-2-1 AMD1[14] on January 2003, and it is now incorporated to into Exif 2.2[15]; the standard file format for DSCs (see http://www.cipa.jp/exifprint/ for details).

On the other hand, several extended-gamut color spaces are recently proposed whose gamut is larger than that of sRGB[16]. Those color spaces were evaluated and compared. AdobeRGB[17], Wide-gamut RGB, and ProPhoto RGB are extended RGB color spaces used in Adobe Photoshop. xvYCC color space[18] is newly proposed at IEC in October 2004. This color space extends its color gamut, while keeping compatibility to the current video coding[19].

3.1. Media-gamut coverage ratio

Here, color patches of various media were used to calculate the ratio of color patches included in the color space. It is named "media-gamut coverage ratio." Table 2 shows the result of evaluation. 769 colors of Munsell Color Cascade (provided by Dr. Pointer, and measured by NPL, UK) were used for surface colors. For the Photography and the Ink Jet, 9x9x9 lattice (= 729 colors) was used, and for the Printing, 928 colors in JapanColor[20] was used. At the last column, coverage ratios for all the patches were calculated.

Table 2: Media gamut coverage ratio for several extended-gamut color spaces

	Media Gamut Cover Ratio				
	Surface	Photo	Ink Jet	Printing	All
sRGB	55.8%	64.2%	62.4%	83.9%	67.5%
AdobeRGB	76.5%	77.0%	82.4%	93.4%	82.9%
WideGamut/RGB	98.0%	87.0%	95.2%	96.1%	94.3%
ProPhoto/RGB	99.6%	90.9%	97.4%	98.4%	96.7%
sYCC	94.3%	93.6%	95.5%	98.7%	95.7%
xvYCC	100.0%	99.9%	99.3%	100.0%	99.8%

It is easily found from the table that sRGB does not have good coverage on any of the media, while sYCC have more than 90% coverage for all of the media. AdobeRGB covers more than 90% for CMYK process ink printing, but does not have enough coverage for other medium. xvYCC has larger coverage ratio than sYCC and it covers almost 100% for all the color patches.

3.2. Quantization Interval

Next, the interval distance between the quantization lattice in each color space was calculated, which we call "quantization interval". If this interval distance in CIELAB color space becomes larger, it will degrade the color gradation and will cause severe color contours in the reproduced images. Average and maximum values of quantization interval between lattices in each color space are reported in Table 3.

Table 3: Quantization interval for several extended-gamut color spaces

	Quantization Interval	
	Ave.	Max.
sRGB	0.472	1.189
AdobeRGB	0.548	1.655
WideGamut/RGB	0.747	2.101
ProPhoto/RGB	0.817	2.498
sYCC	0.701	1.836
[AdobeYCC]	0.830	2.161

For color spaces containing virtual colors (or colors that do not exist), only the lattice inside AdobeRGB's gamut was used for calculations. In addition, since most of DSCs store AdobeRGB images in JPEG file which utilizes YCC encoding space[21] (here, it is named as [AdobeYCC]), quantization interval for [AdobeYCC] is also reported.

3.3. Relation between media-gamut coverage ratio and quantization interval

As easily expected from above discussions, when media-gamut coverage ratio becomes larger quantization interval also becomes larger, and they are in trade-off relationship. For example, Figure 4 indicates the relationship between media-gamut coverage ratio for all color patches and maximum quantization interval.

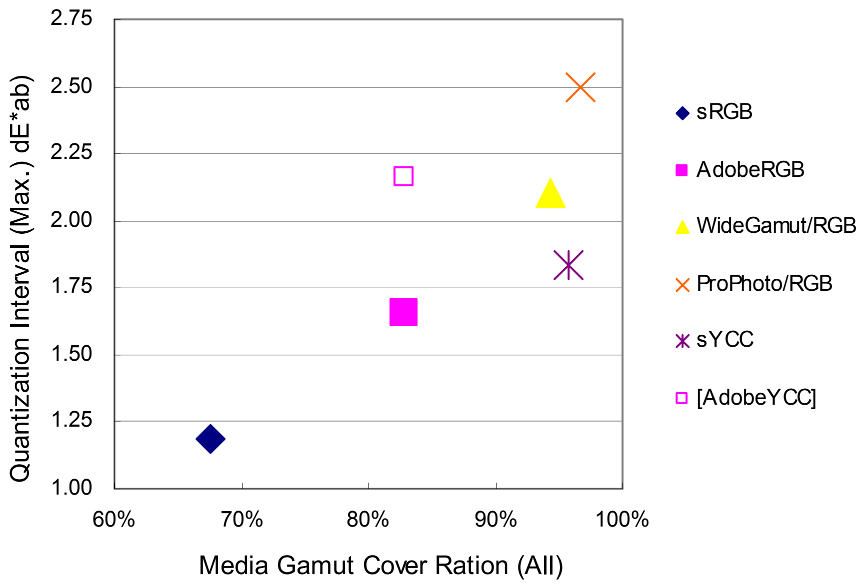

Figure 4. Relationship between Gamut Coverage Ratio and Quantization Interval

sRGB color space has smallest quantization interval with maximum value being less than 1.2 delta E*ab, while its gamut coverage ratio is the smallest among evaluated color spaces. sYCC color space has quantization interval a little larger than AdobeRGB, while its gamut coverage is as good as ProPhotoRGB. From these two aspects, sYCC color space can be regarded as efficient space for storing extended-gamut colors.

4. CONCLUSIONS

In this paper, two-dimensional visualization method for color filter spectral sensitivity evaluation was proposed. Using this method, various color filter sets were compared. Also, extended-gamut color spaces were discussed to store those color images that are captured and processed by DSCs.

As the image quality of digital capturing devices is improving, some of the users are getting unsatisfied with color reproduction within conventional sRGB gamut. On the output device side, color gamut is also extending. Various types of wide-gamut displays are emerging[22] which has much wider gamut than sRGB or even larger than AdobeRGB. Some of consumer ink jet printer now uses Red, Green or Blue inks in addition to CMYK inks to extend its gamut[23]. To transfer colourful images from capturing devices to output devices without loss of information, extended-gamut color space is necessary for the exchange. However, in current situation, colors are sometimes clipped by intermediate PC-based application and/or OS’s graphic library. Total color reproduction system that is capable of transmitting extended-gamut colors without any of color information needs to be defined with well-defined standard color space.

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