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Non-RGB Color Filter Options and Traffic Signal Detection Capabilities

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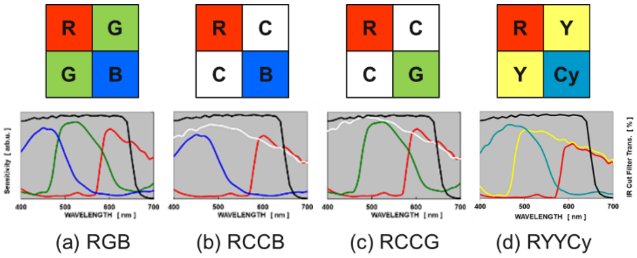
Abstract

Recently, non-RGB image sensors gain a traction in the automotive applications for high sensitivity camera system. Some color filter combinations have been proposed, such as RCCB, RCCG, RYYCy, etc. However, some of them have a difficulty to differentiate Yellow and Red traffic signals. This paper proposes the solution to that issue by shifting Red color filter edge. The differentiation performance was verified by the segmentation in the color space using the traffic signal spectrum database we built up. This result was also checked with image data by using a hyperspectral camera simulation. For the SNR comparison between those color filter options, we propose SNR10-based scheme for an apple-to-apple comparison and discuss on the overall pros / cons.



(a) RGB (b) RCCB (c) RCCG (d) RYYCy

Figure 1. *Popular color filter options in the automotive field*

Introduction

These days, the automotive industry is moving towards higher level of advanced driver assistance systems (ADAS) or autonomous driving systems (ADS) including the detection capability in a long distance, which leads to an increasing demand for smaller-pixel higher-resolution camera [1]. Even with this trend, the customer's demand for low light SNR is kept high. In order to fulfill this demand, non-Red-Green-Blue (RGB) color filter arrays (CFA) are gaining interest [2]. There have been several researches of non-RGB CFA, especially for RGB + Clear [3] [4] aiming at higher sensitivity and good image quality for human vision applications. In the automotive field, another interest is machine vision applications, which led to the introduction of some other CFA options.

Figure 1 shows the current popular CFAs in the automotive field along with the sensitivity spectra: (a) RGB, (b) Red-Clear-Clear-Blue (RCCB), (c) Red-Clear-Clear-Green (RCCG) and (d) Red-Yellow-Yellow-Cyan (RYYCy). RGB is the original standard CFA. RCCB and RCCG are aiming at higher sensitivity utilizing Clear channel. RCCB is the simple replacement of Green channel by Clear channel from RGB. RCCG gives more priority to Green channel signal quality compromising Blue channel compared to RCCB, because Blue is less important than Red and Yellow in automotive machine vision applications. The concept of RYYCy aims at higher sensitivity in two channels replacing Green to Yellow and Blue to Cyan with keeping Red channel to be pure color.

Among those CF options, there is one big issue found in RCCB and RYYCy. Sometimes it is very difficult to differentiate Yellow and Red traffic signals using those CFA [5]. Figure 2 shows an example of Yellow / Red traffic signals detection by the cameras using our RGB and RCCB sensors. In the case of RGB, (a) Yellow signal and (b) Red signal are detected correctly. But in the case of RCCB, both of (c) Yellow signal and (d) Red signal are shown as yellowish and are very difficult to differentiate, although the brightness of the RCCB image is higher than RGB. Traffic signal is one of the most important object to detect in ADAS and ADS. If the image processing part fails to differentiate Yellow and Red traffic signal, it can be fatal for the automotive safety system. So we need some solution to differentiate those colors. There has been some proposal such as modifying the Yellow CF spectrum [5]. However, they did not develop the actual CF. Also the affection of the spectrum modification to the image quality was not discussed.

Figure 2. *Yellow / Red traffic signal detection by RGB camera and RCCB camera.*

In this paper, we first analyze the phenomena by the traffic signal segmentation in color spaces. Then we study the root cause by the spectrum analysis using the worst case traffic signal spectra from our database. Based on that analysis, we propose the modification of Red CF. Effectiveness of this approach is also verified by the segmentation in color spaces based on the measured spectrum of the new CF. We also visually check this effectiveness with a hyperspectral camera simulation. Finally, we do the pros / cons study including image quality parameters and Yellow / Red differentiation capability in order to understand the total picture.

Understanding of the phenomena

Traffic signal light database

Traffic signal differentiation is not solely dependent on the sensitivity spectrum of the camera but also the spectra of the traffic signals, which differs between vendors, regions, etc. So, capturing one or two traffic signals does not give us the conclusion. We need more extensive study. Thus we made a database collecting as many

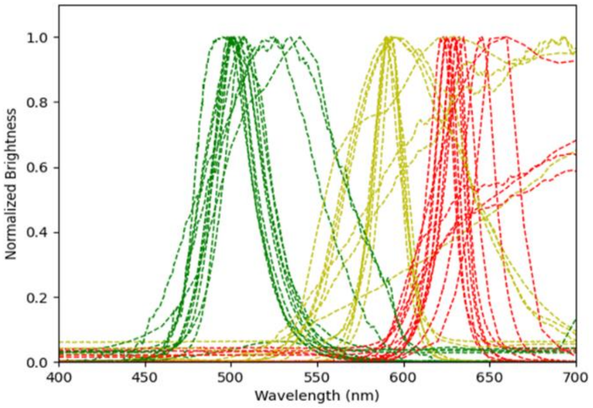


Figure 3. *Traffic light spectra database*

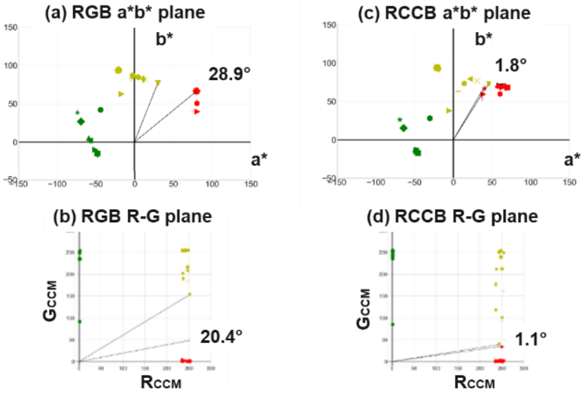


Figure 4. *Traffic light segmentation analysis in color spaces*

traffic signal light spectra as possible from around the world (USA, Europe, Asia), including Light Emitting Diodes (LED) and halogen lamps, from the light source vendor's spec sheet and from our own spectrum measurement. Those spectra are plotted in Fig.3. We can see each of the Green, Yellow and Red colors includes variety of spectra having slightly different peak wavelength and width.

Segmentation analysis in color spaces

In order to analyze Yellow / Red differentiation capability in a quantitative way, we tried to plot those spectra in some color spaces and did a segmentation. The first color space we used was L*a*b*, which has a good correlation with human perception [6].

We explain the formulae used in the transformation taking RCCB as an example. We first applied the white balance (WB) coefficients and color correction matrix (CCM), the coefficients of which were optimized by minimizing the root mean square distance to the target RGB color coordinates (ΔE).

$$\begin{pmatrix} R_{CCM} \\ G_{CCM} \\ B_{CCM} \end{pmatrix} = \begin{pmatrix} Crr & Crc & Crb \\ Cgr & Cgc & Cgb \\ Cbr & Cbc & Cbb \end{pmatrix} \begin{pmatrix} WBr & 0 & 0 \\ 0 & WBc & 0 \\ 0 & 0 & WBb \end{pmatrix} \begin{pmatrix} R \\ C \\ B \end{pmatrix} \tag{1}$$

Then it was transformed into XYZ space as follows.

$$\begin{pmatrix} X_{D65} \\ Y_{D65} \\ Z_{D65} \end{pmatrix} = \begin{pmatrix} 0.412 & 0.358 & 0.181 \\ 0.213 & 0.715 & 0.072 \\ 0.019 & 0.119 & 0.951 \end{pmatrix} \begin{pmatrix} R_{CCM} \\ G_{CCM} \\ B_{CCM} \end{pmatrix} \tag{2}$$

Formulae (1) and (2) can be combined into the following formula.

$$\begin{pmatrix} X_{D65} \\ Y_{D65} \\ Z_{D65} \end{pmatrix} = \begin{pmatrix} Cxr & Cxc & Cxb \\ Cyr & Cyc & Cyb \\ Czr & Czc & Czb \end{pmatrix} \begin{pmatrix} R \\ C \\ B \end{pmatrix} \tag{3}$$

In the case of RGB, this is the formula to transform from RGB to XYZ. But when we think of non-RGB CFA, one of the key concept is to utilize the brightest signal channel to lift up the luminance (Y) channel SNR (YSNR). In this study, we assumed the simplest way to do that by replacing Y channel with Clear channel as follows.

$$\begin{pmatrix} X_{D65} \\ Y_{D65C} \\ Z_{D65} \end{pmatrix} = \begin{pmatrix} Cxr & Cxc & Cxb \\ 0 & (Y_{D65}/C)_{Grey} & 0 \\ Czr & Czc & Czb \end{pmatrix} \begin{pmatrix} R \\ C \\ B \end{pmatrix} \tag{4}$$

With this formula, YSNR was defined by the Clear channel SNR and grey was kept grey in L*a*b* space after the following transformation.

$$\begin{pmatrix} L^* \\ a^* \\ b^* \end{pmatrix} = \begin{pmatrix} 0 & 116 & 0 \\ 500 & -500 & 0 \\ 0 & 200 & -200 \end{pmatrix} \begin{pmatrix} \sqrt[3]{X / Xn} \\ \sqrt[3]{Y / Yn} \\ \sqrt[3]{Z / Zn} \end{pmatrix} - \begin{pmatrix} 16 \\ 0 \\ 0 \end{pmatrix} \tag{5}$$

Traffic signal color segmentation was done by the data projected to the a*b* plane. The representative number was defined by the HUE angle between the Yellow / Red traffic signal regions, i.e., Yellow traffic signal point closest to the Red region and Red traffic signal point closest to the Yellow region.

One more color space we used was the R-G plane derived from the formula (1). This calculation is much simpler than to calculate L*a*b*. So we assumed it represents the calculation for machine vision applications. The segmentation was done with the similar concept as the HUE angle in the a*b* plane.

Figure 4 shows the result. For the case of RGB CFA, the HUE angles between Yellow / Red regions in (a) a*b* plane and (b) R-G plane were as large as 28.9° and 20.4° respectively. So the segmentation should be easily done. On the other hand, for the case of RCCB, the HUE angles between Yellow / Red regions in (c) a*b* plane and (d) R-G plane were as small as 1.8° and 1.1° respectively. That makes it difficult to do the segmentation. So the phenomena shown in Fig. 2 were reproduced in those two color planes, which showed the equivalent result for Yellow / Red differentiation capability.

One more thing to notice is that, some of the individual Yellow / Red points were shown to have big enough HUE angle difference even for RCCB case. But thinking of the automotive safety system, we should compare the worst case combination between Yellow and Red spectra. That is the reason we should be based on the database rather than just a few spectra examples.

Root cause analysis and countermeasure

Spectrum analysis

In order to understand the root cause, we did the spectrum analysis using our RGB and RCCB image sensor's spectra and one of the worst case LED spectra set as shown in Fig. 5. The black lines in (a) (c) (e) are the Yellow LED spectra and those in (b) (d) (f) are the Red LED spectra. The image sensor's sensitivity spectra shown here are with infrared (IR) cut filter at 650nm.

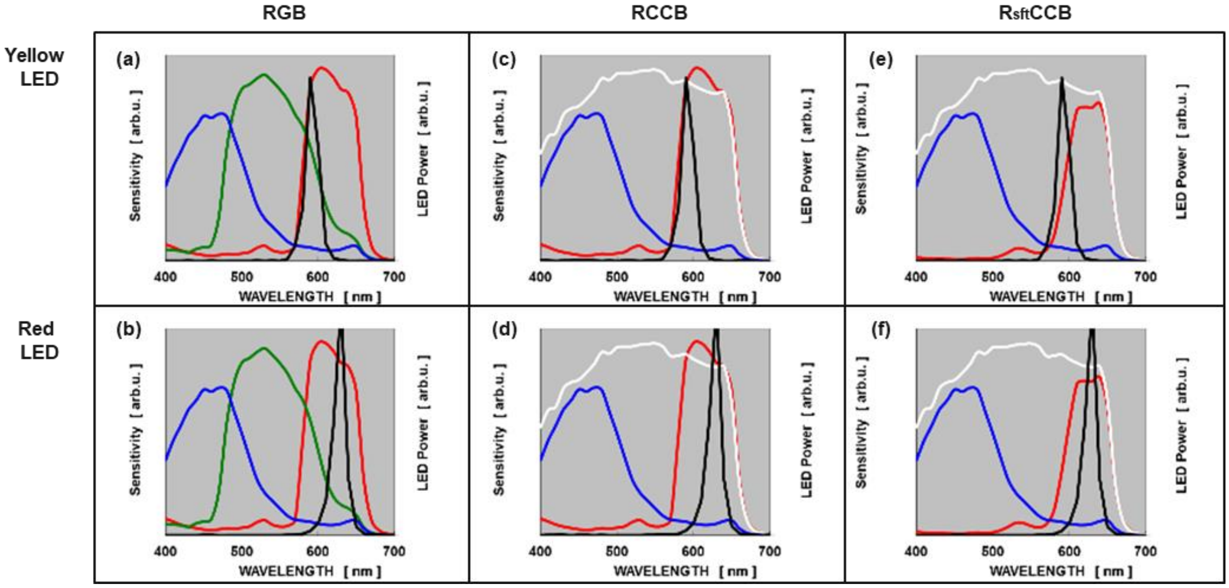


Figure 5. *Spectrum analysis for the root cause study of Yellow / Red detection issue, and the countermeasure*

	Green	Yellow	Red	R / Y Ratio
RGB (R/G)	0.06	1.52	4.69	3.1
RCCB (R/C)	0.05	0.90	1.03	1.1
RsftCCB (Rsft/C)	0.03	0.42	0.89	2.1

Table 1. *R/G and R/C signal ratio for each color traffic signal LED*

Image sensor's output signal is the multiplication of those LED spectra with the sensitivity spectra. With that calculation, the signal ratio between Red and Green channels (R/G) or Red and Clear channels (R/C) for each of Green, Yellow and Red traffic LEDs were calculated and summarized in Table 1. For the case of RGB, R/G ratios for Red LED and Yellow LED were as large as 3.1 times different, whereas R/C ratio in RCCB case had only 1.1 times difference.

That root cause is graphically explained by using Fig. 5. In RGB case, the overlap of (a) Yellow and (b) Red LED spectra to the Green sensitivity spectra are very different. That makes the large difference in R/G number and that is the origin of the color difference in the color space. But in the case of RCCB, both of (c) Yellow and (d) Red LED spectra are within the high sensitivity range in both of Red and Clear sensitivity spectra. That is the reason the difference of R/C ratio is very small. And, since the original data has too small difference, it is very difficult to differentiate the color, even with using any good color processing algorithm.

Countermeasure

Since the root cause was the equivalence of Yellow and Red LED spectra to the current Red and Clear sensitivity spectra, we can improve the Yellow / Red detection capability by modifying either of Red or Clear CF spectrum. This time we propose to shift the Red CF edge 10 – 20nm to longer wavelength side. The Red sensitivity spectrum shown in Fig. 5 (e) (f) are with the newly developed edge-shifted Red (Rsft) CF transmittance. Now the overlap of (e) Yellow and (f) Red LED spectra to the Red sensitivity spectra are very different and the Rsft/C ratio difference between Red LED and Yellow LED became as large as 2.1.

Verification by segmentation in color spaces

In order to verify the Yellow / Red differentiation capability, we did the same segmentation analysis in the color spaces as we discussed in Fig. 4. Figure 6 shows the summary of that study. The top line shows the CFA we studied including RGB, RCCG, RCCB and RYYCy.

The second and fourth lines show the segmentation analysis results in a*b* plane and R-G plane, respectively, with the original Red CF. For RGB and RCCG cases, the HUE angles between Yellow / Red regions were larger than 15°, whereas for RCCB and RYYCy cases, the HUE angles were smaller than 5°.

Thus we introduced the Rsft CF, which are shown as the dashed lines in the graphs of those two CF. The third and fifth lines show the results with Rsft CF in a*b* plane and R-G plane, respectively. The HUE angles between Yellow / Red regions were larger than 24°. Thus the effectiveness of introducing the Rsft CF was proven using the traffic signal spectra database.

Hyperspectral camera simulation

We also checked the appearance of the upper results by camera simulation as shown in Fig. 7. For this purpose, we established a hyperspectral camera simulator utilizing a public hyperspectral database [7], and placed traffic signal graphics in the scene. As of the traffic signal, all the lights are shown as ON for easy comparison of color. The traffic signal data was selected from one of the worst case LED spectra set.

In the case of (a) RGB and (b) RCCG, the color difference between Red, Yellow and Green signals are clearly seen, although Green is shifted to yellow green in RCCG compared to RGB. In the case of (c) RCCB and (d) RYYCy with original Red spectrum, both of Red and Yellow traffic signals look orange-ish and the color difference is small. By introducing the Rsft CF, both of (e) RsftCCB and (f) RsftYYCy show clear Red and Yellow colors.

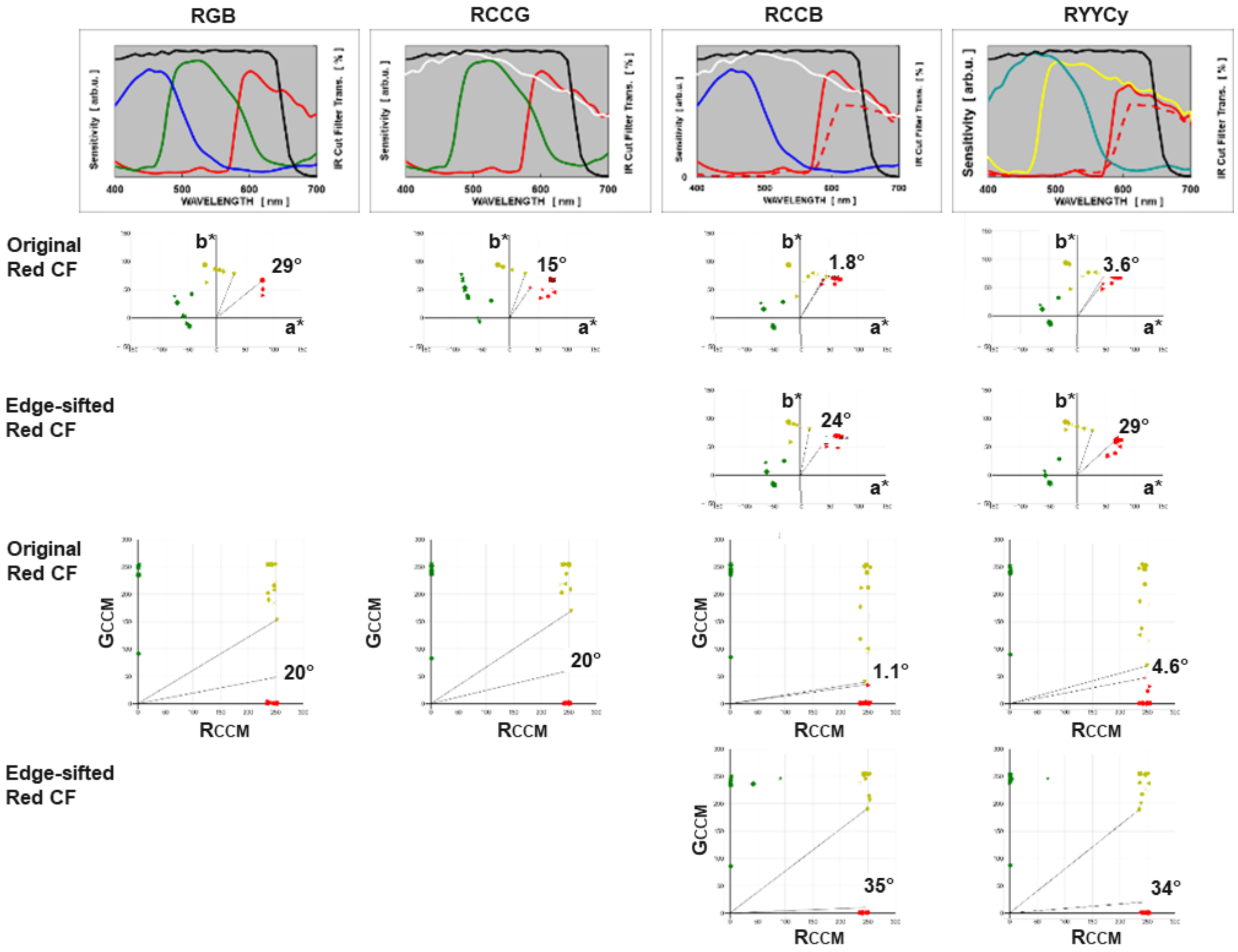


Figure 6. *Yellow / Red differentiation capability verification with edge-shifted Red sensitivity spectrum introduction*

Figure 7. *Appearance verification using hyperspectral camera simulation*

One more thing to notice is that the color reproduction of the overall scene is not significantly changed form (c) to (e) or from (d) to (f). That means the edge shift in Red sensitivity spectrum does not significantly degrade the image quality.

Pros / Cons study of color filter options

Finally, we did a pros / cons study including image quality parameters and Yellow / Red differentiation capability in order to understand the total picture of the overall color filter options.

Luminance SNR10 and Visual SNR10

In order to do the apple-to-apple image quality comparison with a simple representative number, we utilized Luminance SNR10 (YSNR10) and Visual SNR10 (VSNR10) concepts.

YSNR10 is defined as the lux level at which the SNR of luminance channel becomes ten for 18% grey patch [8] [9]. The luminance data was derived from the formula (3) for RGB case and the formula (4) for non-RGB cases. This is a convenient parameter to represent the image quality and used in many places, especially in the mobilephone market. One drawback is that it doesn't include the color noise component. So, sometimes it doesn't represent the image quality appearance to human eyes. Thus we propose the VSNR10 concept utilizing the Visual Noise (VN) specification proposed by the ISO 15739 group [10].

We explain the parameters for the VN calculation in this study using Fig. 8. The transformation block diagram defined by the ISO 15739 group is shown in (a). The center part is the Contrast Sensitivity Function (CSF) Filtering calculation, which corresponds to the contrast appearance to human eyes for each color and each spatial frequency components. A, C_1, C_2 are the color components to be used in the CSF calculation. The transformation between XYZ and AC_1C_2 are defined as follows [11].

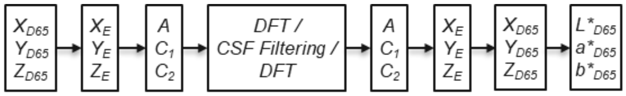
$$\begin{pmatrix} A \\ C_1 \\ C_2 \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & -1 & 0 \\ 0 & 0.4 & -0.4 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \tag{6}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 1 & 1 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & -2.5 \end{pmatrix} \begin{pmatrix} A \\ C_1 \\ C_2 \end{pmatrix} \tag{7}$$

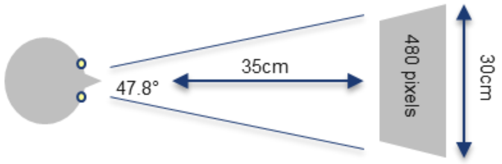
In the case of image data, Discrete Fourier Transformation (DFT) is required to transform the data into frequency domain. In the case of this study, we don't need DFT since we don't handle image data. For the simplicity of calculation, we just calculate the white noise component in the frequency domain. But we still need to define the spatial frequency amount to calculate the noise.

For this purpose, a configuration of noise observation was defined as shown in (b), thinking of the condition that each pixel's noise is effectively observed by human eyes, i.e., a monitor having 30cm width and showing 480 pixels horizontally (ex. 4×4 pixel block makes one displayed pixel in 1080 monitor) is observed from 35cm distance. This case, the field of view is 47.8° and the highest spatial frequency defined by the pixel pitch is 5 cycles / degree. The white noise component up to this spatial frequency is shown as the blue-hatched rectangle area in the graph of (c). Since the CSF for each of A, C_1 and C_2 color components are defined as shown in the same graph, the CSF of this system is calculated as the multiplication of the blue-hatched white noise and those three curves. The calculation results were 0.869, 0.970 and 0.619 for A, C_1 and C_2, respectively. In the end, combining with the formulae (6) and (7), the core part of the calculation from $X_EY_EZ_E$ back to $X_EY_EZ_E$ in the block diagram (a) is expressed by the simple matrix calculation as follows.

(a) Transformations to calculate Visual Noise



(b) Spatial frequency condition to calculate Contrast Sensitivity Function



(c) Contrast Sensitivity Function and White Noise

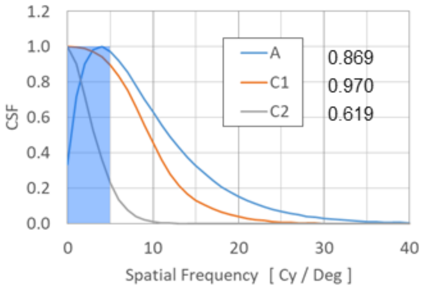


Figure 8. *Visual Noise Calculation Parameters*

$$\begin{pmatrix} X_{Ec} \\ Y_{Ec} \\ Z_{Ec} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & -2.5 \end{pmatrix} \begin{pmatrix} 0.869 & 0 & 0 \\ 0 & 0.970 & 0 \\ 0 & 0 & 0.619 \end{pmatrix} \begin{pmatrix} 0 & 1 & 0 \\ 1 & -1 & 0 \\ 0 & 0.4 & -0.4 \end{pmatrix} \begin{pmatrix} X_E \\ Y_E \\ Z_E \end{pmatrix} \tag{8}$$

After calculating L*a*b* by the formula (5), VN is calculated with the following formula.

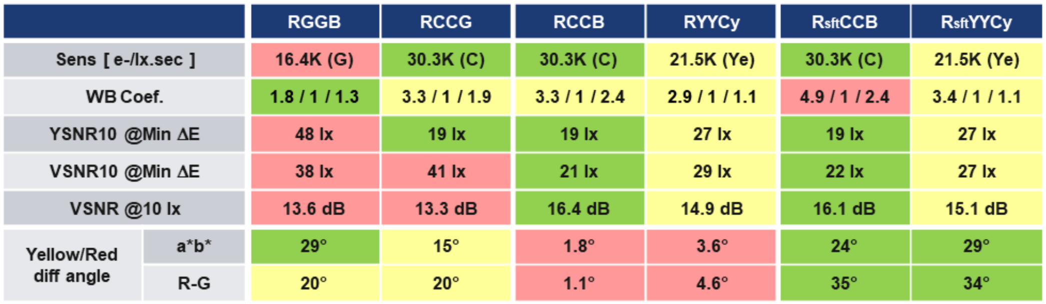
$$VN = \sqrt{(\sigma_{L^*})^2 + (0.338 \cdot \sigma_{a^*})^2 + (0.395 \cdot \sigma_{b^*})^2} \tag{9}$$

Finally, VSNR10 is defined as the lux level at which the VSNR becomes ten for 18% grey patch. Since we still assume 18% grey chart for VSNR10, the signal component of a* and b* are zero. So this definition corresponds to the following formula.

$$\frac{L^*}{\sqrt{(\sigma_{L^*})^2 + (0.338 \cdot \sigma_{a^*})^2 + (0.395 \cdot \sigma_{b^*})^2}} = 10 \tag{10}$$

Pros / Cons study result

Table 2 shows the total pros / cons of the CF options including image quality parameters and the HUE angles between Yellow / Red regions. It was calculated under D65 illumination condition. Sensitivity was calculated from the quantum efficiency of the brightest channel. WB coefficient was calculated from the sensitivity ratio between color channels. Other parameters used in YSNR10 and VSNR10 calculation were 18% grey chart, F 1.8 lens, IR cut filter at 650nm, 2.1um pixel size and 1/60 second exposure time. We also calculated the VSNR at 10 lux condition.



		RGGB	RCCG	RCCB	RYYCy	RsftCCB	RsftYYCy
Sens [e-/lx.sec]		16.4K (G)	30.3K (C)	30.3K (C)	21.5K (Ye)	30.3K (C)	21.5K (Ye)
WB Coef.		1.8 / 1 / 1.3	3.3 / 1 / 1.9	3.3 / 1 / 2.4	2.9 / 1 / 1.1	4.9 / 1 / 2.4	3.4 / 1 / 1.1
YSNR10 @Min ΔE		48 lx	19 lx	19 lx	27 lx	19 lx	27 lx
VSNR10 @Min ΔE		38 lx	41 lx	21 lx	29 lx	22 lx	27 lx
VSNR @10 lx		13.6 dB	13.3 dB	16.4 dB	14.9 dB	16.1 dB	15.1 dB
Yellow/Red diff angle	a*b*	29°	15°	1.8°	3.6°	24°	29°
	R-G	20°	20°	1.1°	4.6°	35°	34°

Table 2. *Total pros / cons of color filter options including image quality parameters and Yellow / Red differentiation capability*

The color of each cell is roughly indicating the pros / cons of each of the color filter options for each parameters. And the overall trend seen from this table is summarized as follows.

- Rsft CF solves the Yellow / Red differentiation issue. VSNR10 is not affected, or it is even improved a little in RYYCy case. But the WB coefficient gets larger.
- RCCB has the benefit in lowest VSNR10 number. But Rsft CF makes WB coefficient too large.
- Overall, RsftYYCy has the best balance among those non-RGB CF options in this study.

Conclusion

We studied Yellow / Red traffic signal detection issue and non-RGB CF options from various points of view. We proposed shifting the Red CF spectrum edge to longer wavelength side to improve Yellow / Red differentiation. We verified the effectiveness of the newly developed Red CF spectrum response by the segmentation analysis in a*b* plane and R-G plane based on the traffic signal spectrum database we established. In order to check the image data, we also established a hyperspectral image simulation and checked the appearance. Overall pros / cons of the CF options were discussed with introducing YSNR10 and VSNR10 concepts. Among the non-RGB CF options popular in the automotive market, RsftYYCy had the best balance.

With having all those studies, we could see the total picture of the non-RGB CF options based on device parameter comparison. It can be a useful method to study any non-RGB CF options.

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