https://doi.org/10.2352/ISSN.2470-1173.2020.10.IPAS-134

Color Interpolation Algorithm for a Periodic White-Dominant RGBW Color Filter Array

Kyeonghoon Jeong, Jonghyun Kim, and Moon Gi Kang; School of Electrical and Electronic Engineering, Yonsei University; 50 Yonsei-ro, Seodaemun-gu, Seoul 03722, Republic of Korea

Abstract

Recently, CFA sensors including the W channel have been developed. Since the W channel receives luminance information, the W channel has a wider spectrum band than that of the R, G, and B channels. Therefore, the W channel can get higher SNR than that of the R, G, and B channels. There are many color interpolation methods for the Bayer CFA, but less for the RGBW CFA. In this paper, we propose a new color interpolation method for white-dominant RGBW CFA. The proposed method is edge-adaptive. Its method reconstruct the W channel first which has a high sampling rate. Next, the R, G, and B channels are reconstructed by using the color difference domains with the W channel. Experimental results show that the PSNR and visual confirmation are higher than the conventional method.

Introduction

Most digital and smartphone cameras use an RGB color filter array (CFA) as shown in Fig. 1 (a) [1], where R, G, and B means red, green, and blue respectively. In a single sensor camera with CFA, each pixel is stored with only one of the RGB values, the other two pixel values must be interpolated. This interpolation process is typically called the demosaicing process. It plays a critical role in producing high quality color images. Most color interpolation algorithms based on the Bayer CFA interpolate the missing G first, since the number of the G pixels is twice as large as those of the R and B pixels. Then we find R and B. There are several ways to interpolate R and B, and the most popular one is the way using color ratio [2], [3], and another is using color difference domains [4], [5], [6].

In the past literatures, many algorithms using color difference interpolation have been proposed because of its simplicity of implementation. The assumption of this algorithm is that all color bands have spectral correlations and the color difference has a similar image at the texture and at the edges. Therefore, high frequency energy is further reduced in the color difference domain (e.g. G - R and G - B) than in each color channel. For this reason, the interpolation algorithm using the color difference domain increases the accuracy of demosaicing when compared with the accuracy of demosaicing for each channel.

As the number of pixels increased in these days, a degradation of the sensitivity problem occurred. W pixels can absorb more photons than R,G, and B pixels, so they have higher PSNR values contrast to R, G, and B pixels in low light images, where W means white. As a result, RGBW CFA was proposed. There are many RGBW CFA with high sensitivity sensors such as the Kodak 2.0 4x4 RGBW CFA (Fig. 1 (b)) and the Sony 4x4 RGBW CFA (Fig. 1 (c)). Also, color interpolation algorithm for RGBW CFA was proposed [7]. The previous RGBW CFA has 50% W pixels compared to the total pixels.

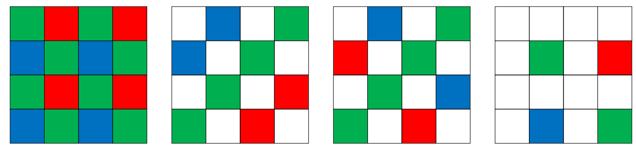


Figure 1. *(a) The Bayer CFA. [1] (b) Kodak 2.0 4-by-4 RGBW CFA. [8] (c) Sony 4-by-4 RGBW CFA. [9] (d) Periodic white-dominant RGBW CFA.*

In this paper, we propose the white-dominant RGBW CFA which has 75% W pixels compared to the total pixels (Fig. 1 (d)) and its corresponding color demosaicing algorithm to restore the full color image from the new RGBW CFA shown in Fig. 1 (d). Section gives the proposed overall algorithm for color interpolation. First, we reconstruct the W channel using directional color difference domain. After reconstructing W channel, we reconstruct each R, G, B channels by using the correlation between R, G, B, and W channels. In Section , experimental results are shown, including comparisons with conventional method. Finally, we conclude the paper in Section .

Proposed method

The proposed algorithm starts by finding the missing W pixels. After reconstructing W, the RGB channels are obtained using the correlation of the W and RGB channel. By using the high-sensitive W channel, we determine the edge direction and interpolate the pixels.

W channel interpolation

The W channel should be interpolated first. It is important to reconstruct the W pixels because they have 75% of the total pixels, and the W channel has a large frequency correlation with other RGB channels. The algorithm is implemented in two steps. First, we perform the interpolation for each channel in the vertical and horizontal directions, and estimate the color difference. Since the interpolation takes into account inter-channel correlation, high quality color images are reconstructed. Second, the north, south, east and west directions are determined using the color difference gradient values. For white and green rows and columns in the input pattern image, we interpolate the missing pixel using bilinear filter. The directional estimates for the missing white and green

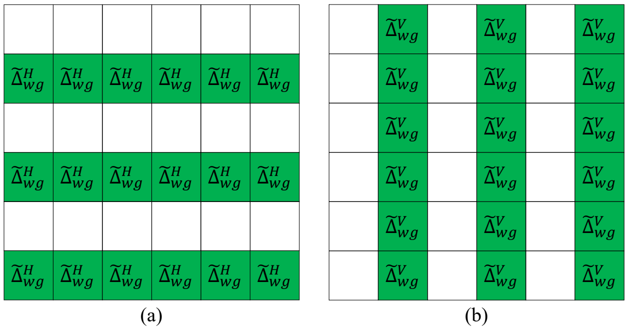


Figure 2. *(a) Horizontal color difference map (b) Vertical color difference map.*

pixel values are:

$$\tilde{W}^H_{i,j} = \begin{cases} \dfrac{W_{i,j-1}+W_{i,j+1}}{2}, & \text{at the R,G,B pixels} \\ W_{i,j}, & \text{at the W pixel,} \end{cases}$$
$$\tilde{W}^V_{i,j} = \begin{cases} \dfrac{W_{i-1,j}+W_{i+1,j}}{2}, & \text{at the R,G,B pixels} \\ W_{i,j}, & \text{at the W pixel.} \end{cases} \tag{1}$$

$$\begin{aligned} &\tilde{G}^V(i,j) = \mathbf{f}_i . G(i-3:i+3,j), \\ &\tilde{G}^H(i,j) = G(i,j-3:j+3).\mathbf{f}_i', \\ &\quad \mathbf{f}_i = [\tfrac{1}{4} \quad \tfrac{1}{2} \quad \tfrac{3}{4} \quad 1 \quad \tfrac{3}{4} \quad \tfrac{1}{2} \quad \tfrac{1}{4}]. \end{aligned} \tag{2}$$

The estimates for blue and red pixels are calculated in the same way. The next step is to calculate the horizontal and vertical color differences shown as Fig. 2 using the pixel values from the original and the estimated by direction:

$$\tilde{\Delta}^H_{w,g}(i,j) = \begin{cases} \tilde{W}^H_{i,j} - G_{i,j}, & W \text{ is interpolated} \\ W_{i,j} - \tilde{G}^H_{i,j}, & G \text{ is interpolated,} \end{cases}$$
$$\tilde{\Delta}^V_{w,g}(i,j) = \begin{cases} \tilde{W}^V_{i,j} - G_{i,j}, & W \text{ is interpolated} \\ W_{i,j} - \tilde{G}^V_{i,j}, & G \text{ is interpolated,} \end{cases} \tag{3}$$

where V and H denote horizontal and vertical directions and (i,j) is the pixel location. Similarly, the vertical and horizontal difference $(W-B, W-R)$ is obtained. For the W channel interpolation, we have directional color difference estimates in (3), and we combine them accordingly.

$$\begin{aligned} \hat{\Delta}_{w,g}(i,j) = [&w_V.\mathbf{f}_u.\tilde{\Delta}^V_{w,g}(i-2:i+2,j) \\ &+ w_H.\tilde{\Delta}^H_{w,g}(i,j-2:j+2).\mathbf{f}_u']/w_C, \\ w_C = w&_V + w_H, \\ \mathbf{f}_u = [&\tfrac{1}{4} \quad 0 \quad \tfrac{1}{2} \quad 0 \quad \tfrac{1}{4}]. \end{aligned} \tag{4}$$

The weights for each vertical and horizontal directions are calculated as follows by using a local window size of 5 by 5:

$$\begin{aligned} w_V &= 1/\left(\sum_{k=i-2}^{i+2}\sum_{l=j-2}^{j+2} D^V(k,l)\right)^2, \\ w_H &= 1/\left(\sum_{k=i-2}^{i+2}\sum_{l=j-2}^{j+2} D^H(k,l)\right)^2, \end{aligned} \tag{5}$$

where gradients are defined as:

$$\begin{aligned} D^V_{i,j} &= \left|\tilde{\Delta}^V_{i-1,j} - \tilde{\Delta}^V_{i+1,j}\right|, \\ D^H_{i,j} &= \left|\tilde{\Delta}^H_{i,j-1} - \tilde{\Delta}^H_{i,j+1}\right|. \end{aligned} \tag{6}$$

The final color difference of W and G is obtained by using (4) calculated above,. The four neighbors and its own weight are used to estimate the desired pixel difference:

$$\begin{aligned} \tilde{\Delta}_{w,g}(i,j) = [&w_N.\hat{\Delta}_{w,g}(i-2,j) + w_S.\hat{\Delta}_{w,g}(i+2,j) \\ &+ w_E.\hat{\Delta}_{w,g}(i,j+2) + w_W.\hat{\Delta}_{w,g}(i,j-2)]/w_T, \\ w_T = w_N &+ w_S + w_W + w_E. \end{aligned} \tag{7}$$

The weights (w_N, w_S, w_E, w_W) are calculated in a similar way to the other weights (w_V, w_H) obtained in (5). Using a local window size of 5 by 5 for the horizontal and vertical direction:

$$\begin{aligned} w_N &= 1/\left(\sum_{k=i-4}^{i}\sum_{l=j-2}^{j+2} D^V(k,l)\right)^2, \\ w_S &= 1/\left(\sum_{k=i}^{i+4}\sum_{l=j-2}^{j+2} D^V(k,l)\right)^2, \\ w_E &= 1/\left(\sum_{k=i-2}^{i+2}\sum_{l=j}^{j+4} D^H(k,l)\right)^2, \\ w_W &= 1/\left(\sum_{k=i-2}^{i+2}\sum_{l=j-4}^{j} D^H(k,l)\right)^2. \end{aligned} \tag{8}$$

The color differences between W and R and W and B are also estimated in the above method. Once the color difference is determined, we add the difference to each pixels for estimation of W value:

$$\begin{aligned} \tilde{W}(i,j) &= R(i,j) + \tilde{\Delta}_{w,r}(i,j), \\ \tilde{W}(i,j) &= G(i,j) + \tilde{\Delta}_{w,g}(i,j), \\ \tilde{W}(i,j) &= B(i,j) + \tilde{\Delta}_{w,b}(i,j). \end{aligned} \tag{9}$$

G channel interpolation

The G channel uses a method similar to the method of estimating the W channel. Because of the white-dominant CFA, the estimated W channel has a large similar correlation with the original W channel. Therefore, the color differences are updated using the estimated W at the R, G, and B pixels location. Estimation of the G channel has three steps.

First, we interpolate the G pixels at the R and B pixels location. Second, the center pixel of the restored G pixels. Finally interpolate the rest pixels.

$$\tilde{\Delta}^{H^{update}}_{w,g}(i,j) = \begin{cases} \dfrac{\tilde{\Delta}^H_{w,g}(i-1,j) + \tilde{\Delta}^H_{w,g}(i+1,j)}{2}, & \text{even rows} \\ \tilde{\Delta}^H_{w,g}(i,j), & \text{odd rows,} \end{cases}$$
$$\tilde{\Delta}^{V^{update}}_{w,g}(i,j) = \begin{cases} \dfrac{\tilde{\Delta}^V_{w,g}(i,j-1) + \tilde{\Delta}^V_{w,g}(i,j+1)}{2}, & \text{even rows} \\ \tilde{\Delta}^V_{w,g}(i,j), & \text{odd rows.} \end{cases} \tag{10}$$

We use (3) to estimate the G pixels at the R and B pixels. The horizontal and vertical differences obtained in (3) are empty at even rows and even columns, respectively. These empty rows and columns are interpolated by bilinear interpolation to make the entire horizontal and vertical difference map. We use the updated horizontal and vertical directions in (10) to interpolate in a similar way of the previous W channel interpolation method. The updated color difference of W and G is obtained as below:

$$\begin{aligned}\tilde{\Delta}_{w,g}^{update}(i,j) = [&w_N^{update}.\hat{\Delta}_{w,g}^{update}(i-2,j)\\ &+w_S^{update}.\hat{\Delta}_{w,g}^{update}(i+2,j)\\ &+w_E^{update}.\hat{\Delta}_{w,g}^{update}(i,j+2)\\ &+w_W^{update}.\hat{\Delta}_{w,g}^{update}(i,j-2)]/w_T^{update},\\ w_T^{update} = w_N^{update} &+ w_S^{update} + w_W^{update} + w_E^{update},\end{aligned} \tag{11}$$

where (11) means the results that we use the method of Section based on (10).

The final estimates of the G channel are as below:

$$\tilde{G}(i,j) = \begin{cases} W(i,j) - \tilde{\Delta}_{w,g}(i,j), & \text{at } W \text{ pixel},\\ \tilde{W}(i,j) - \tilde{\Delta}_{w,g}(i,j), & \text{at } R,G,B \text{ pixel}.\end{cases} \tag{12}$$

R and B channel interpolation

We reconstruct the missing diagonal pixels like R pixel values at B locations and B pixel values at R locations for R and B channel interpolation. These pixels are interpolated by simple lowpass filter size of 5 by 5:

$$\begin{aligned}\tilde{R}(i,j) &= \tilde{W}(i,j)\\ &\quad - \tilde{\Delta}_{w,r}(i-2:i+2, j-2:j+2) \otimes \mathbf{H}_{lpf},\\ \tilde{B}(i,j) &= \tilde{W}(i,j)\\ &\quad - \tilde{\Delta}_{w,b}(i-2:i+2, j-2:j+2) \otimes \mathbf{H}_{lpf},\\ \mathbf{H}_{lpf} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 1\\ 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0\\ 1 & 0 & 0 & 0 & 1\end{bmatrix} \cdot \frac{1}{4},\end{aligned} \tag{13}$$

where $\otimes$ denotes element-wise matrix multiplication and subsequent summation. The R and B pixels at green locations are interpolated by the R and B pixel value including its estimated value above (13). We estimate the remaining pixels in a similar way.

Experimental results

The performance of the proposed method is measured with the Kodak data set shown in Fig. 3. The white-dominant RGBW CFA was generated by subsampling a full color image. The W channel was estimated by the average of the R, G, and B channels:

$$W(i,j) = \frac{R(i,j)+G(i,j)+B(i,j)}{3}. \tag{14}$$

In quantitative comparison, it shows better performance than the modified conventional method [5], the edge directional method. We modified the conventional method [5], because the method is based on the Bayer CFA. And it also shows better performance than the recently conventional method [10]. The results are summarized in the table below by comparing the peak signal-to-noise ratio (PSNR). PSNR is defined as follows:

$$PSNR = 10\log_{10}\frac{255^2}{MSE}, \tag{15}$$

where MSE means the mean squared error between the original and the output image. As shown in Table 1, the proposed algorithm performs better in edge regions. Comparing the average PSNR of the given Table 1, we can see that it is 5dB higher than the conventional method.

The qualitative analysis compared the experimental results in the areas where color interpolation errors can be caused by high frequency components. In particular, Fig. 4 (a) is part of Image 5 and Fig. 4 (e) is part of Image 6 with the parrot's eye. From the results of the proposed method, it can be seen that the false color is reduced as shown in Fig. 4 (d), (h) by accurately estimating the color difference. Experimental results show that the reconstructed image obtained by applying the proposed algorithm to the white-dominant RGBW is superior to the image reconstructed by the conventional method in terms of SNR and visual confirmation.

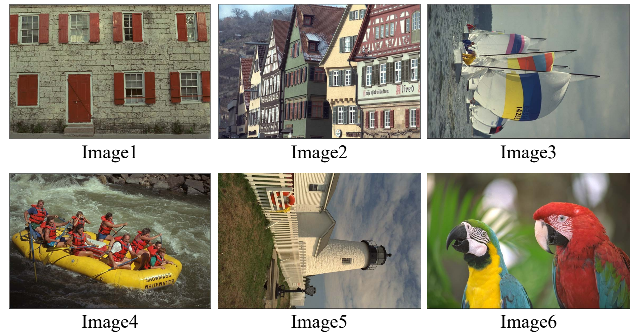


Figure 3. *Test images(Kodak dataset).*

Comparison of CPSNR (dB) values for the conventional method and the proposed method

Name	Conventional [5]	Conventional [10]	Proposed
Image1	29.43	32.59	36.44
Image2	27.33	32.30	35.15
Image3	35.66	36.66	40.26
Image4	31.50	30.06	32.56
Image5	31.35	34.61	39.15
Image6	36.66	30.10	38.44
Average	31.99	32.72	37.00

Concolusion

In this paper, we propose an optimized color interpolation method for white-dominant CFA to acquire high resolution and high sensitivity images simultaneously. In this case, the edge adaptive technique is used, and the color difference between the W channel and the R, G, and B channels using spectral correlation and W channel advantages is utilized. As there are few conven-

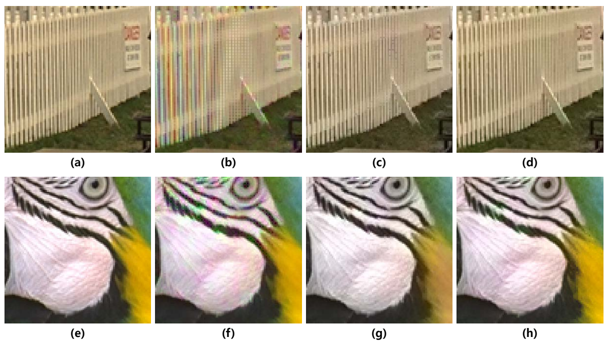


Figure 4. *Partially magnified experimental results : (a), (e) original image, and (b), (f) modified conventional method [5], and (c), (g) modified conventional method [10], and (d), (h) proposed method.*

tional methods based on periodic white-dominant CFA, it is found that the proposed algorithm outperforms conventional methods in terms of SNR and visual confirmation when compared with the method based on [5] and [10]. It is expected to be applied to low light cameras or surveillance cameras to increase sensitivity and obtain high resolution images.

References

[1] B. E. Bayer, “Color imaging array,” U.S. Patent 3 971 065, Jul. 20, 1976.

[2] R. Kimmel, “Demosaicing: image reconstruction from color ccd samples,” IEEE Transactions on Image Processing, vol. 8, no. 9, pp. 1221–1228, Sep. 1999.

[3] R. Lukac and K. N. Plataniotis, “Color filter arrays: design and performance analysis,” IEEE Transactions on Consumer Electronics, vol. 51, no. 4, pp. 1260–1267, Nov 2005.

[4] I. Pekkucuksen and Y. Altunbasak, “Gradient based threshold free color filter array interpolation,” in 2010 IEEE International Conference on Image Processing, Sep. 2010, pp. 137–140.

[5] W. Lu and Y.-P. Tan, “Color filter array demosaicking: new method and performance measures,” IEEE Transactions on Image Processing, vol. 12, no. 10, pp. 1194–1210, Oct 2003.

[6] K. Hirakawa and T. W. Parks, “Adaptive homogeneity-directed demosaicing algorithm,” IEEE Transactions on Image Processing, vol. 14, no. 3, pp. 360–369, March 2005.

[7] J. Kim and M. G. Kang, “Color interpolation algorithm for the sony-rgbw color filter array,” in Electronic Imaging, Image Processing: Algorithms and Systems XVI, vol. 2018, no. 13, 2018.

[8] M. Kumar, E. O. Morales, J. E. Adams, and Wei Hao, “New digital camera sensor architecture for low light imaging,” in 2009 16th IEEE International Conference on Image Processing (ICIP), Nov 2009, pp. 2681–2684.

[9] I. Hirota, “Solid-state imaging device, method for processing signal of solid-state imaging device, and imaging apparatus,” U.S. Patent 20 100 141 812A1, Jun. 10, 2010.

[10] P. Oh and S. Lee, and M. G. Kang, ”Colorization-Based RGB-White Color Interpolation using Color Filter Array with Randomly Sampled Pattern,” Sensors 2017, 17, 1523.

Acknowledgments

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. 2019R1A2C2002167).

Author Biography

Kyeonghoon Jeong received his BS degree in Electrical and Electronic Engineering from Yonsei University of Korea (2017). He is currently pursuing a PhD degree through the School of Electrical and Electronic Engineering at Yonsei University. His current research interests are color interpolation and contrast enhancement.

Jonghyun Kim received his BS degree in electrical and electronic engineering from Yonsei University, South Korea, in 2012. He is currently pursuing a PhD degree with the Department of Electrical and Electronic Engineering at Yonsei University. His current research interests include superresolution image processing, color interpolation and image restoration.

Moon Gi Kang received Ph.D. degree in electrical engineering from Northwestern University, USA in 1994. He is currently a professor at the Department of Electronic Engineering of Yonsei University, Korea. He has served as the Editor of SPIE Milestone Series Volume (CCD and CMOS imagers), the Guest Editor of the IEEE SP Magazine Special Issue on Superresolution Image Reconstruction (May 2003), the Associate Editors of the EURASIP Journal of ASP and the Elsevier Journal of Digital Signal Processing.

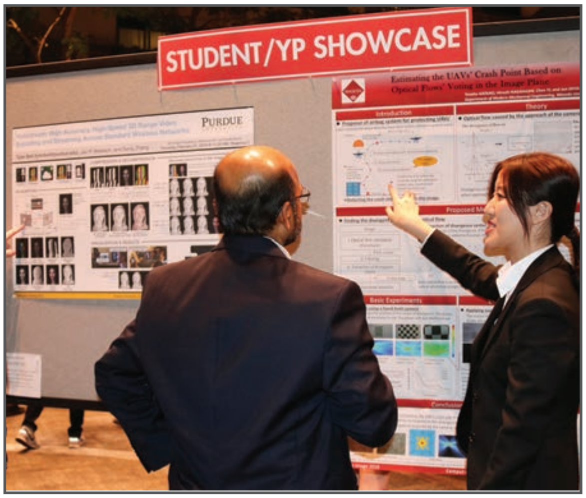
JOIN US AT THE NEXT EI!

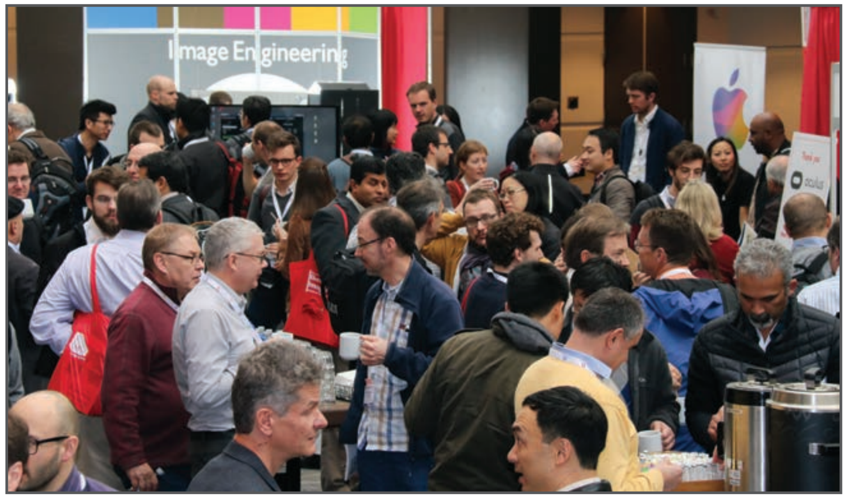
IS&T International Symposium on

Electronic Imaging

SCIENCE AND TECHNOLOGY

Imaging across applications . . . Where industry and academia meet!





• SHORT COURSES • EXHIBITS • DEMONSTRATION SESSION • PLENARY TALKS •
• INTERACTIVE PAPER SESSION • SPECIAL EVENTS • TECHNICAL SESSIONS •

www.electronicimaging.org

IS&T
imaging.org