https://doi.org/10.2352/ISSN.2470-1173.2018.13.IPAS-439

Color Interpolation Algorithm for the Sony-RGBW Color Filter Array

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Abstract

Recently, a CFA sensor including a W channel has been developed. Since the W channel receives brightness information, it has a broad spectrum band compared to primary colors (Red, Green, Blue) and exhibits a high SNR. A camera using the CFA sensor obtains only certain type of color information for each pixel, so a color interpolation method is used to restore the full resolution image. In this paper, we propose a new color interpolation method for Sony-RGBW CFA. The proposed method is edge-adaptive and preferentially restores the W channel with a high sampling rate. In the next step, the R, G, and B channels are restored in the color difference domain using the W channel with the full resolution. Experimental results showed that the reconstructed image obtained by applying the proposed algorithm to the Sony-RGBW is superior to the image restored by conventional method in terms of SNR and visual confirmation.

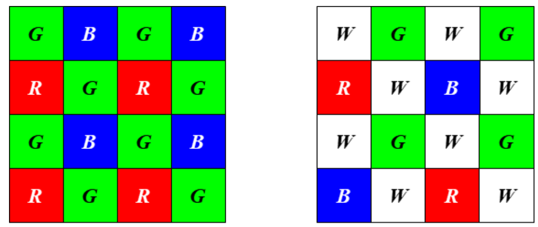
Introduction

Most digital cameras based on a single sensor use a color filter array (CFA) to obtain full color images. The Bayer CFA [1] shown in Figure 1 (a) is a typical pattern among CFAs. This CFA acquires one color information at each pixel, which is a set of primary colors composed of Red (R), Green (G), and Blue (B) channels. Color interpolation is essential to estimate the full color image from the CFA image. However, the results of color interpolation cause artifacts such as zipper effect, color aliasing and moire in complex edge regions. To overcome the resolution degradation of the interpolated results, several color interpolation algorithms [2, 3] were developed to improve the spatial resolution.

Recently CFAs including a White (W) channel as well as primary colors have been developed [4, 5]. Since the W channel receives the brightness information, it has a broader spectral band than the R, G, and B channels that acquire a specific wavelength band. Therefore, it exhibits high sensitivity and has an advantage of being robust to noise. It has a higher SNR than the primary colors acquired at the same exposure time in low light conditions. In addition, motion blur can be reduced because a shorter exposure time is required to obtain the same amount of light. Among the CFAs including the W channel, the Sony-RGBW CFA [6] shown in Figure 1 (b) has a regular structure of 4x4 units in which the W channel occupies 50% of total pixels, and the G channel occupies 25% and the R / B channels occupy 12.5%.

As various CFAs have been developed, algorithms that can be applied to CFAs containing W channels have been developed. There is such a frequency domain approach [7], variational approach [8], regularization approach [9] and so on. However, these algorithms have the advantage of being widely applicable to various CFAs, but they are not optimized for specific CFAs.

Also, since the Sony-RGBW CFA is structurally different from the Bayer CFA, the existing color interpolation methods [2, 3] for the Bayer CFA cannot be used. Therefore, a new color interpolation method optimized for this CFA should be needed.



(a) (b)

Figure 1. *(a) the Bayer CFA, (b) Sony-RGBW CFA*

In this paper, the color interpolation is proposed to restore the full resolution image from the Sony-RGBW CFA shown in Figure 1 (b). First, the W channel is reconstructed using directional color difference information. Then, a full color image is reconstructed by using the correlation between R, G, B, and W channels. The rest of this paper is organized as follows. Section 2 gives the proposed overall algorithm. In Section 3, experimental results are shown, including comparisons with conventional method. Finally, we conclude the paper in Section 4.

Proposed Method

The proposed method begins with W channel interpolation. After estimating the W channel, the RGB channels are obtained using the correlation of the W and the RGB channels. The edge direction estimation, which is the most important part of the edge-adaptive color interpolation scheme, could be accurately performed by utilizing the W channel with high sensitivity.

W Channel Interpolation:

The W channel should be initially interpolated, because the W channel with the highest sampling rate occupies most of the spatial resolution of the CFA image. In addition, since the W channel is the highest sensitivity channel, it is effective to interpolate the R, G, and B channels based on interpolated W channel.

The algorithm can be divided into three stages. First, the color difference information is estimated by performing initial interpolation in a vertical / horizontal direction. Second, the directional color difference estimates are combined using the direction of the edge based on the color difference information and the chrominance information corresponding to the position of each pattern. Finally, color difference estimates are improved by compensating high frequency in diagonal edge.

In order to interpolate in consideration of inter-channel correlation, chrominance information between the W channel and another channel is required. It is necessary to interpolate all channels by direction. In this algorithm, initial interpolation is performed in the vertical and horizontal directions for each channel, thereby maximizing the resolution obtained in each direction. This is relatively effective for interpolation of R and B channels with low sampling rates. And chrominance information is estimated from the initially interpolated W and color channels.

For white & red rows and columns in the input pattern image, the directional estimates for the missing white and red pixel values are:

$$\begin{aligned}
\widetilde{W}^{Ver}(i,j) &= \mathbf{f_W} \cdot W(i-1:i+1,j),\\
\widetilde{W}^{Hor}(i,j) &= W(i,j-1:j+1) \cdot \mathbf{f_W}^T,\\
\widetilde{R}^{Ver}(i,j) &= \mathbf{f_R} \cdot R(i-3:i+3,j),\\
\widetilde{R}^{Hor}(i,j) &= R(i,j-3:j+3) \cdot \mathbf{f_R}^T,\\
\mathbf{f_W} &= [1/2 \quad 1 \quad 1/2],\\
\mathbf{f_R} &= [1/4 \quad 1/2 \quad 3/4 \quad 1 \quad 3/4 \quad 1/2 \quad 1/4],
\end{aligned} \tag{1}$$

where *Ver* and *Hor* denote horizontal and vertical directions and (i,j) is the pixel location. For every pixel coordinate, two directional estimates are obtained using the convolution operation with simple low-pass filters. The directional color difference estimates are obtained by taking their difference as follows:

$$\begin{aligned}
\tilde{\Delta}_{W,R}^{Ver}(i,j) &= \begin{cases} \widetilde{W}^{Ver}(i,j) - R(i,j), & \text{at R pixel} \\ W(i,j) - \widetilde{R}^{Ver}(i,j), & \text{at W pixel} \end{cases},\\
\tilde{\Delta}_{W,R}^{Hor}(i,j) &= \begin{cases} \widetilde{W}^{Hor}(i,j) - R(i,j), & \text{at R pixel} \\ W(i,j) - \widetilde{R}^{Hor}(i,j), & \text{at W pixel} \end{cases},
\end{aligned} \tag{2}$$

where $\tilde{\Delta}_{W,R}^{Ver}$ and $\tilde{\Delta}_{W,R}^{Hor}$ stand for the vertical and horizontal difference estimates between W and R channels. Estimations of the directional color difference estimates for B and G channels are calculated in the same manner. Gradients are useful for estimating direction information from images. Since the gradient values in the similar region are small and otherwise large, so it is used to estimate the direction of the edge or the direction of the high frequency information. The absolute color difference gradients are calculated by:

$$\begin{aligned}
D^{Ver}(i,j) &= \left| \tilde{\Delta}_{W,R}^{Ver}(i-1,j) - \tilde{\Delta}_{W,R}^{Ver}(i+1,j) \right|,\\
D^{Hor}(i,j) &= \left| \tilde{\Delta}_{W,R}^{Hor}(i,j-1) - \tilde{\Delta}_{W,R}^{Hor}(i,j+1) \right|,
\end{aligned} \tag{3}$$

where D^{Ver} and D^{Hor} stands for the vertical and horizontal color difference gradients. For initial W channel interpolation, the directional color difference estimates are combined adaptively as follows:

$$\begin{aligned}
\hat{\Delta}_{W,C}(i,j) &= \omega_N \tilde{\Delta}_{W,C}^{Ver}(i-2,j) + \omega_S \tilde{\Delta}_{W,C}^{Ver}(i+2,j)\\
&\quad + \omega_E \tilde{\Delta}_{W,C}^{Hor}(i,j+2) + \omega_W \tilde{\Delta}_{W,C}^{Hor}(i,j-2),
\end{aligned} \tag{4}$$

where $\omega_N, \omega_S, \omega_E, \omega_W$ are the weights for each direction of the edge. The following is the process of determining the direction of the edge from the estimated vertical / horizontal chrominance information.

$$\begin{aligned}
\omega_N &= 1 \Big/ \left(\sum_{C \in (R,G,B)} \sum_{y=i-3}^{i} \sum_{x=j-2}^{j+2} \left| \Delta_{W,C}^{Ver}(y,x) \right| \times \left| D^{Ver}(y,x) \right| \right)^2,\\
\omega_S &= 1 \Big/ \left(\sum_{C \in (R,G,B)} \sum_{y=i}^{i+3} \sum_{x=j-2}^{j+2} \left| \Delta_{W,C}^{Ver}(y,x) \right| \times \left| D^{Ver}(y,x) \right| \right)^2,\\
\omega_E &= 1 \Big/ \left(\sum_{C \in (R,G,B)} \sum_{y=i-2}^{i+2} \sum_{x=j}^{j+3} \left| \Delta_{W,C}^{Hor}(y,x) \right| \times \left| D^{Hor}(y,x) \right| \right)^2,\\
\omega_W &= 1 \Big/ \left(\sum_{C \in (R,G,B)} \sum_{y=i-2}^{i+2} \sum_{x=j-3}^{j} \left| \Delta_{W,C}^{Hor}(y,x) \right| \times \left| D^{Hor}(y,x) \right| \right)^2.
\end{aligned} \tag{5}$$

We combine the directionality of the edge through the derivative of the color difference information and the similarity of the W channel and the color channel, and set the weight by taking the reciprocal of this value. That is, the direction having a larger value is the direction of the edge. The weights $\omega_N, \omega_S, \omega_E, \omega_W$ for each direction are calculated by combining gradients of color difference estimates and the similarity of color over a local window.

The following is a step to reinforce the diagonal edge. Since the W channel has the shape of a quincuncial pattern, the entire image is restored through a combination of vertical and horizontal directions. This results in a higher resolution in the vertical and horizontal direction, but inevitably leads to a lower resolution in the diagonal direction. However, it is possible to improve W channel results by compensating the diagonal direction region. At this time, overshooting is prevented by not performing additional high frequency compensation in the vertical and horizontal directions. Improved color difference estimates are obtained by compensating high frequency as follows:

$$\begin{aligned}
\tilde{\Delta}_{W,R}(i,j) &= \hat{\Delta}_{W,R}(i,j)\\
&\quad + \sum_{(i+a,j+b) \in S_R} \alpha_{i+a,j+b} (R(i,j) - R(i+a,j+b)),
\end{aligned} \tag{6}$$

where α represents the weight for each direction and is calculated as follows:

$$\begin{aligned}
\alpha_{i-1,j-1} &= \omega_{NE} / (\omega_N + \ldots + \omega_W + \omega_{NE} + \ldots + \omega_{SW}),\\
\alpha_{i+1,j-1} &= \omega_{SE} / (\omega_N + \ldots + \omega_W + \omega_{NE} + \ldots + \omega_{SW}),\\
\alpha_{i-1,j+1} &= \omega_{NW} / (\omega_N + \ldots + \omega_W + \omega_{NE} + \ldots + \omega_{SW}),\\
\alpha_{i+1,j+1} &= \omega_{SW} / (\omega_N + \ldots + \omega_W + \omega_{NE} + \ldots + \omega_{SW}),\\
\alpha_{i-1,j} &= 0, \alpha_{i+1,j} = 0, \alpha_{i,j-1} = 0, \alpha_{i,j+1} = 0.
\end{aligned} \tag{7}$$

After the color difference estimates are improved, this value is added to the target pixel to obtain the estimated W channel value:

$$\widetilde{W}(i,j) = C(i,j) + \tilde{\Delta}_{W,C}(i,j), \tag{8}$$

where C stands for each color channel (R, G, and B). In the above equations, the positions of R channel pixel are exemplified, but the pixel positions of the G and B channels are expressed in a similar manner.

RGB Channel Interpolation:

In this step, RGB color interpolation is performed using the W channel with the full resolution interpolated in the previous step. Since the RGBW sensor occupies a small proportion of the R, G, and B channels, it is necessary to fully utilize the information of the W channel. First, interpolation is performed by increasing the sampling rate step by step. When this part is analyzed in frequency domain, the signal components that are repeated according to the sampling rate are removed step by step to remove the aliasing of the image.

In order to utilize the correlation between the R, G, B, and W channels, a method using the color difference between channels is used. It is assumed that the color difference between two channels is constant in a certain region. That is, assuming that the values of $W-R$, $W-G$ and $W-B$ are constant, the inter-channel correlation is considered by interpolating the difference value between the current pixel and the neighboring pixel.

$$\widetilde{C}(i,j)=\widetilde{W}(i,j)+\sum_{(i+a,j+b)\in S_C}\omega_{i+a,j+b}\widetilde{\Delta}_{W,C}(i+a,j+b), \tag{9}$$

where $\widetilde{W}$ is the W channel estimated in the previous step, ω and $\widetilde{\Delta}_{W,C}$ are weight and color difference information for the direction of the edge. The weight ω for each direction is calculated as follows:

$$\begin{aligned}\omega_{i-1,j}=1/(1&+\left|\widetilde{W}(i-1,j)-\widetilde{W}(i,j)\right|\\&+\left|\widetilde{W}(i-2,j)-\widetilde{W}(i-1,j)\right|\\&+\left|\widetilde{W}(i-1,j-1)-\widetilde{W}(i,j-1)\right|/2\\&+\left|\widetilde{W}(i-2,j-1)-\widetilde{W}(i-1,j-1)\right|/2\\&+\left|\widetilde{W}(i-1,j+1)-\widetilde{W}(i,j)\right|/2\\&+\left|\widetilde{W}(i-2,j+1)-\widetilde{W}(i-1,j)\right|),\\\omega_{i-1,j-1}=1/(1&+\left|\widetilde{W}(i-2,j-2)-\widetilde{W}(i-1,j-1)\right|\\&+\left|\widetilde{W}(i-1,j-1)-\widetilde{W}(i,j)\right|\\&+\left|\widetilde{W}(i-1,j-2)-\widetilde{W}(i,j-1)\right|/2\\&+\left|\widetilde{W}(i-2,j-1)-\widetilde{W}(i-1,j)\right|/2.\end{aligned} \tag{10}$$

The weights for other directions are represented by similar rules. In the proposed algorithm, interpolation of R, G, and B channels is performed by increasing the sampling rate step by step, and chrominance information is used to consider the correlation with the W channel. This has the effect of reducing artifacts due to the resolution degradation for each channel.

Experimental Results

The performance of the proposed method was evaluated using the Kodak dataset shown in Figure 2. The Sony-RGBW CFA was generated by sub-sampling the CFA from the full color image. It is assumed that the W channel is the average of the R, G, and B channels as follows:

Figure 2. Tested images (Kodak dataset)

$$W_{i,j}=\frac{(R_{i,j}+G_{i,j}+B_{i,j})}{3}. \tag{11}$$

In the quantitative comparison, the proposed algorithm has better performance than the conventional method such as variational approach [8]. The peak signal-to-noise ratio (PSNR) comparison results for the interpolated results were summarized in Table 1. The PSNR is defined as:

$$PSNR=10\log_{10}\frac{255^2}{MSE}, \tag{12}$$

where MSE represents the mean squared error between the original and resulting images. As shown in Table 1, the proposed algorithm outperformed the conventional method, especially in images with lots of edge regions. Its average PSNR is higher than the conventional method by 1.57dB.

For the qualitative analysis, experimental results were compared for area where color interpolation errors are likely to occur because of high frequency components. In particular, Figure 3 (a) is a part of the Image 7 (Kodak 19 image), in which there is a continuous vertical edge in the fence. In the results of the proposed method, the false color or grid effect decreases as shown in Figure 3 (c), (f), and (i) by estimating the color difference accurately.

Experimental results showed that the reconstructed image obtained by applying the proposed algorithm to Sony-RGBW is superior to the image restored by conventional method in terms of SNR and visual confirmation.

Comparison of CPSNR values for the conventional method and the proposed method

Name	Conventional [8]	Proposed
Image 1	33.82	35.88
Image 2	36.91	37.34
Image 3	32.92	34.35
Image 4	39.66	41.33
Image 5	33.29	35.31
Image 6	40.14	41.08
Image 7	37.31	38.77
Image 8	38.72	41.31
Average	36.60	38.17

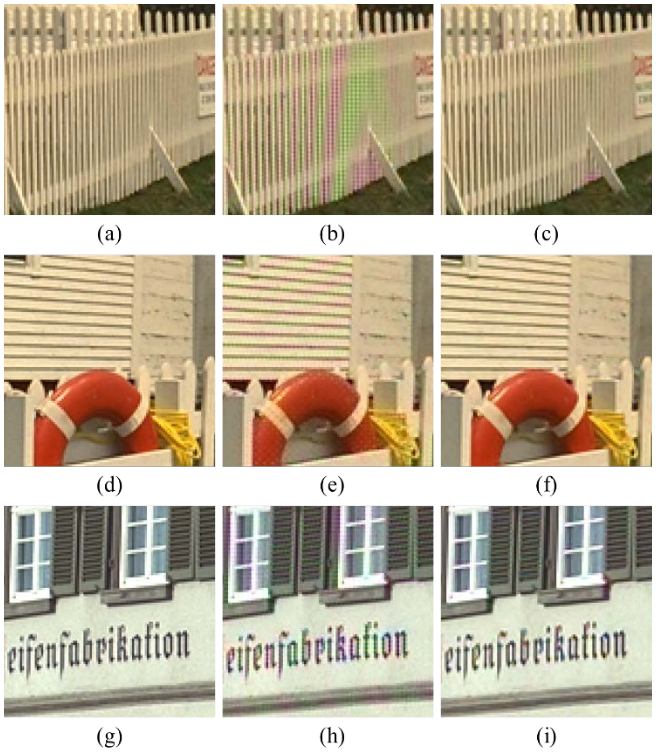


Figure 3. Partially magnified experimental results: (a), (d), (g) original image, and (b), (e), (h) conventional method [8], and (c), (f), (i) proposed method.

Conclusions

In this paper, we propose a color interpolation method optimized for the Sony-RGBW CFA to simultaneously acquire high-resolution and high-sensitivity images. In this case, edge-adaptive technique is utilized, and the W-channel and the R, G, and B channels are used in the difference domain to utilize the spectral correlation and utilize the advantages of the W channel. In addition, to solve the aliasing artifact problem that can frequently occur in the Sony-RGBW CFA, the method of compensating high frequency in the diagonal area is proposed. Experimental results showed that the reconstructed image obtained by applying the proposed algorithm to Sony-RGBW is superior to the image restored by conventional method in terms of SNR and visual confirmation. This is expected to be applied to cameras for low illumination or surveillance cameras to increase sensitivity and obtain the high resolution image.

Acknowledgments

This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Science, ICT and Future Planning (No. 2015R1A2A1A14000912)

References

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

[2] I. Pekkucuksen and Y. Altunbasak, "Multiscale gradients-based color filter array interpolation," *IEEE Trans. Image Process.*, vol. 22, no. 1, pp. 157–165, Jan. 2013.

[3] D. Kiku, Y. Monno, M. Tanaka, and M. Okutomi, "Residual interpolation for color image demosaicking," *in 2013 IEEE International Conference on Image Processing*, Sep. 2013.

[4] K. Hirakawa and P. J. Wolfe, "Spatio-spectral color filter array design for optimal image recovery," *IEEE Trans. Image Process.*, vol. 17, no. 10, pp. 1876–1890, Oct. 2008.

[5] P. Hao, Y. Li, Z. Lin, and E. Dubois, "A geometric method for optimal design of color filter arrays," *IEEE Trans. Image Process.*, vol. 20, no. 3, pp. 709–722, Mar. 2011.

[6] I. Hirota, "Solid-state imaging device, method for processing signal of solid-state imaging device, and imaging apparatus," U.S. Patent 8 436 925, May 2013.

[7] D. Alley, S. Susstrunk, and J. Herault, "Linear demosaicing inspired by the human visual system," *IEEE Trans. Image Process.*, vol. 14, no. 4, pp. 439–449, Apr. 2005.

[8] L. Condat, "A generic variational approach for demosaicking from an arbitrary color filter array," *in 2009 IEEE International Conference on Image Processing*, Nov. 2009.

[9] D. Menon and G. Calvagno, "Regularization approaches to demosaicking," *IEEE Trans. Image Process.*, vol. 18, no. 10, pp. 2209–2220, Oct. 2009.

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