

LETTER

Pattern Transformation Method for Digital Camera with Bayer-Like White-RGB Color Filter Array

Jongjoo PARK[†], Nonmember and Jongwha CHONG^{†a)}, Member

SUMMARY A Bayer-like White-RGB (W-RGB) color filter array (CFA) was invented for overcoming the weaknesses of commonly used RGB based Bayer CFA. In order to reproduce full-color images from the Bayer-like W-RGB CFA, a demosaicing or a CFA interpolation process which estimates missing color channels of raw mosaiced images from CFA is an essential process for single sensor digital cameras having CFA. In the case of Bayer CFA, numerous demosaicing methods which have remarkable performance were already proposed. In order to take advantage of both remarkable performance of demosaicing method for Bayer CFA and the characteristic of high-sensitive Bayer-like W-RGB CFA, a new method of transforming Bayer-like W-RGB to Bayer pattern is required. Therefore, in this letter, we present a new method of transforming Bayer-like W-RGB pattern to Bayer pattern. The proposed method mainly uses the color difference assumption between different channels which can be applied to practical consumer digital cameras.

key words: Bayer-like White-RGB, color filter array interpolation, W-RGB demosaicing, pattern transformation

1. Introduction

While the resolution of digital cameras is increasing, the size of complementary metal-oxide semiconductor (CMOS) image sensors remains limited. As a result of this trend, CMOS image sensors now contain a huge number of pixels; however, the size of each sensor array, color filter array (CFA) [1], is becoming increasingly smaller. Therefore, degradation of light sensitivity by each element can lead to deterioration in image quality, especially in low-light conditions. To overcome this weakness, a sensor with a higher sensitivity is required. To address this need, a White-RGB (W-RGB) CFA, which has a greater sensitivity than a conventional Bayer CFA, was developed [2].

Examples of CFA patterns are shown in Fig. 1. A Bayer-like W-RGB CF, Fig. 1 (b), substitutes one green filter array on every 2×2 matrix of the Bayer CFA, Fig. 1 (a), with a white filter array which is made by transparent resin films. These white filter arrays can be penetrated by all visible light with wavelengths of 450-700 nm. Namely, white filter arrays on the W-RGB CFA enable penetration of all color (red, green and blue) intensities, while other pixels do not. Consequently, the existence of the white filter arrays themselves improves sensitivity of the W-RGB sensors [2]. In order to transform Bayer-like W-RGB pattern to Bayer

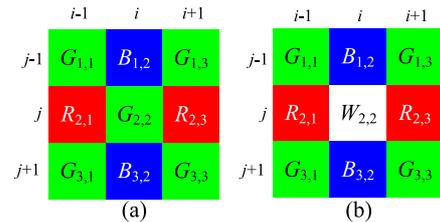


Fig. 1 Examples of CFA patterns: (a) Bayer, (b) Bayer-like W-RGB

pattern for adopting numerous Bayer demosaicing method which have remarkable performance, a new method of transforming Bayer-like W-RGB pattern to Bayer pattern is required. Therefore, a new transformation method is proposed in this letter.

2. Related Work

Many demosaicing methods for the conventional Bayer CFA have been proposed until now; however, few methodologies for dealing with W-RGB have been proposed because the researches of W-RGB are at early stage until now. The conventional methods for W-RGB CFA can be classified into three categories: (1) Color separation method, (2) training method and (3) virtual color filter method. Color separation methods estimate missing red, green, and blue channels at white sample locations using color ratio of neighboring pixels [3]. They firstly assume that the value of the white raw sample is the same as the value of the sum of red, green and blue sample values at the same pixel location. Furthermore, they also suppose that the value of the raw white sample is similar to the sum of the neighboring red, green and blue sample values, for example, an equation $W_{2,1} \approx R_{2,2} + G_{1,2} + B_{1,1}$, which can be referred to in Fig. 1 (b), will be also satisfied. With the supposition, they estimate missing red, green, and blue channels at the white locations based on the color ratio of neighboring pixels using the equations as follows:

$$X_W = W \times \frac{X_{average}}{(R_{average} + G_{average} + B_{average})} \quad (1)$$

where $X_{average}$ represents the average intensities of red, green, and blue located near the white target pixel, and X_W represents the estimated red, green, and blue channels at white locations. This method is ineffective when edges occur near the white target pixels; therefore, edge-adaptive

Manuscript received December 18, 2014.

Manuscript revised June 18, 2015.

Manuscript publicized August 11, 2015.

[†]The authors are with the Department of Electronics Engineering, Hanyang University, Seoul, Rep. of Korea.

a) E-mail: jchong@hanyang.ac.kr (Corresponding author)

DOI: 10.1587/transinf.2014EDL8249

method was proposed for avoiding blur defect near the target white pixels [3]. Edge-adaptive method estimates three channels at white target locations if edges are not detected; otherwise, the method interpolates only green channels at the white samples for avoiding serious blur effect. Although edge adaptive method considers the edges, it is still not sufficient for avoiding blur. Also, the assumption of the method, $W_{i,j} \approx R_{i,j} + G_{i,j} + B_{i,j}$, is not satisfied in real-life situation.

Training method pre-defines logical functions for estimating missing channels at white locations [5]. By comparing the values from the functions with values from a real-device, the missing channel can be estimated. However, the way of defining logical functions is hidden. Virtual color filter method extracts missing color channels from white spectrum at the wavelength of 400-700 nm using pre-defined virtual color filter models [6]. In order to build these models, an image of a reference color spectrum board which is captured by a W-RGB CFA is required. This method is the simplest way for W-RGB CFA; however, it is found to be inadequate for applying to real-device because it was not proposed using RGB colorimetric system.

These conventional methods for W-RGB CFA remain poorly understood because the researches are at early stage now. Therefore, in this paper, we will propose a detailed pattern transformation method for W-RGB CFA.

3. Proposed Transformation Method

The proposed method described in the following sections consists of two main steps: (1) extraction of edge information and (2) estimation of missing green channel at white sample locations.

For the sake of notation of a pixel at (i, j) in the Bayer-like W-RGB image, capitalized $W_{i,j}$, $R_{i,j}$, $G_{i,j}$, and $B_{i,j}$ are used to denote the already known white, red, green and blue and notations written in small letter, $w_{i,j}$, $r_{i,j}$, $g_{i,j}$ and $b_{i,j}$ denote the unknown values of corresponding color channels in the image. In addition, we pre-define the directional representations which are used throughout the whole paper. We will use six directional parameters: North-east (NE), north-west (NW), south-east (SE), south-west (SW), diagonal 1 (D1), diagonal 2 (D2).

3.1 Extraction of Edge Information

Sharpness near the object edges plays an important role for the human visual system. Therefore, it is important to avoid

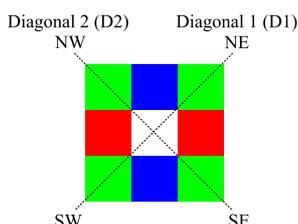


Fig. 2 The directional representations used for the proposed method.

averaging across edge structures to prevent the appearance of blur near the edges. To that end, edge information should be calculated in advance. A commonly used method of expressing edge information utilizes the differences in luminance between adjacent pixels. This method, however, is not reasonable for use in the case of the mosaiced image where only one of three or four color channels is available for each pixel location. In order to express edge information in this situation, an edge strength filter is used [7]. Edge strength at pixel location $(2, 2)$, referred in Fig. 1 (b), for example, can be calculated using the equation as follows:

$$S_{2,2} = \frac{|G_{1,1} - G_{3,3}|}{2} + \frac{|G_{1,3} - G_{3,1}|}{2} + |B_{1,2} - B_{3,2}| + |R_{2,1} - R_{2,3}| \quad (2)$$

where $S_{2,2}$ denotes the edge strength at pixel location $(2, 2)$. The edge strengths at the other locations can be calculated in the same way simply, by replacing W , R and B according to the structure of the pattern. The resulting map using Eq. (2) contains only the information of strength at every location, do not contain the information of direction. In order to extract the information of edge direction from the pre-calculated edge strength map, we use the equations as follows:

$$E_{D(i,j)} = \begin{cases} D1, & \text{if } D_{D1(i,j)} > D_{D2(i,j)} \\ D2, & \text{otherwise} \end{cases}$$

$$\begin{cases} D_{D1(i,j)} = \sum_{m=-2}^1 \left(\sum_{n=-1}^2 (S_{i+m-1,j+n} - S_{i+m,j+n-1}) \right) \\ D_{D2(i,j)} = \sum_{m=-2}^1 \left(\sum_{n=-2}^1 (S_{i+m,j+n} - S_{i+m-1,j+n+1}) \right) \end{cases} \quad (3)$$

where $E_{D(i,j)}$ denotes the edge directions at (i, j) , and $D_{x(i,j)}$ is the total cost toward x direction at (i, j) . By comparing the adjacent edge strength costs which lie on corresponding direction themselves, the target location is labeled D1 if $D_{D1(i,j)}$ is larger than $D_{D2(i,j)}$ and vice versa.

3.2 Estimation of Missing Green at White Locations

The first step of estimating missing green starts with calculating the color differences between different channels at (i, j) . The color differences of white-green diagonal can be defined as follows:

$$\begin{cases} \Delta C_{g,w(i,j)}^{D1} = \tilde{g}_{i,j}^{D1} - W_{i,j}, & \text{if } E_{D(i,j)} = D1 \\ \Delta C_{g,w(i,j)}^{D2} = \tilde{g}_{i,j}^{D2} - W_{i,j}, & \text{if } E_{D(i,j)} = D2 \end{cases} \quad (4)$$

where $\Delta C_{g,w(i,j)}^{D1}$ and $\Delta C_{g,w(i,j)}^{D2}$ denote the color differences between green and white at (i, j) . At the white locations, we already know the values of the white from the raw mosaiced input image while green channels do not; therefore, we use the already known term of $W_{i,j}$ and unknown term of $g_{i,j}$. Using the Eq. (4), it is required to estimate the unknown $\tilde{g}_{i,j}^x$, green channel estimator, at white target locations for achieving color difference; therefore, we firstly use the Laplacian

interpolation filter [9] as follows:

$$\left\{ \begin{aligned} \tilde{g}_{i,j}^{D1} &= \frac{G_{i-1,j+1} + G_{i+1,j-1}}{2} + \frac{2 \times W_{i,j} - W_{i-2,j+2} - W_{i+2,j-2}}{4}, \\ &\quad \text{if } E_{D(i,j)} = D1 \\ \tilde{g}_{i,j}^{D2} &= \frac{G_{i-1,j-1} + G_{i+1,j+1}}{2} + \frac{2 \times W_{i,j} - W_{i-2,j-2} - W_{i+2,j+2}}{4}, \\ &\quad \text{if } E_{D(i,j)} = D2 \end{aligned} \right. \quad (5)$$

The reason why we consider only the diagonal directions in the case is because green color filter elements lie on diagonally from the white color filter elements in the center, referred in Fig. 1 (b).

Equation (4) limit the scope to pixel location (i, j) only; we can extend the equations for including adjacent pixels along to the same direction, the Eq. (4) can be modified as follows:

$$\left\{ \begin{aligned} \Delta C_{g,w,(i,j)}^{D1} &= \frac{\Delta C_{g,w,(i-1,j+1)}^{D1}}{N_1} + \frac{\Delta C_{g,w,(i,j)}^{D1}}{N_2} + \frac{\Delta C_{g,w,(i+1,j-1)}^{D1}}{N_3}, \\ &\quad \text{if } E_{D(i,j)} = D1 \\ \Delta C_{g,w,(i,j)}^{D2} &= \frac{\Delta C_{g,w,(i-1,j-1)}^{D2}}{N_1} + \frac{\Delta C_{g,w,(i,j)}^{D2}}{N_2} + \frac{\Delta C_{g,w,(i+1,j+1)}^{D2}}{N_3}, \\ &\quad \text{if } E_{D(i,j)} = D2 \end{aligned} \right. \quad (6)$$

where $\Delta C_{g,w,(i,j)}^{Dx}$ denotes the extended color channel difference estimation at (i, j) , and N_x denotes normalizing factor. Rewrite form of Eq. (6) can be written as follows:

$$\left\{ \begin{aligned} \Delta C_{g,w,(i,j)}^{D1} &= \frac{G_{i-1,j+1} - \tilde{w}_{i-1,j+1}^{D1}}{4} + \frac{\tilde{g}_{i,j}^{D1} - W_{i,j}}{2} \\ &\quad + \frac{G_{i+1,j-1} - \tilde{w}_{i+1,j-1}^{D1}}{4}, \quad \text{if } E_{D(i,j)} = D1 \\ \Delta C_{g,w,(i,j)}^{D2} &= \frac{G_{i-1,j-1} - \tilde{w}_{i-1,j-1}^{D2}}{4} + \frac{\tilde{g}_{i,j}^{D2} - W_{i,j}}{2} \\ &\quad + \frac{G_{i+1,j+1} - \tilde{w}_{i+1,j+1}^{D2}}{4}, \quad \text{if } E_{D(i,j)} = D2 \end{aligned} \right. \quad (7)$$

Each element in the Eq. (7) is normalized by the distance between their operands. The extended equations of the color channel differences assumption, Eq. (7), are required to estimate $\hat{w}_{i,j}^x$, the white channel estimator at green pixel location, even though the white channel is unnecessary for full-color image using RGB color space. The equation of white channel estimator at target green sample location (i, j) can be calculated using the Laplacian interpolation filter as follows:

$$\left\{ \begin{aligned} \tilde{w}_{i,j}^{D1} &= \frac{W_{i-1,j+1} + W_{i+1,j-1}}{2} + \frac{2 \times G_{i,j} - G_{i-2,j+2} - G_{i+2,j-2}}{4}, \\ &\quad \text{if } E_{D(i,j)} = D1 \\ \tilde{w}_{i,j}^{D2} &= \frac{W_{i-1,j-1} + W_{i+1,j+1}}{2} + \frac{2 \times G_{i,j} - G_{i-2,j-2} - G_{i+2,j+2}}{4}, \\ &\quad \text{if } E_{D(i,j)} = D2 \end{aligned} \right. \quad (8)$$

By modifying the equations of color differences estimation, Eq. (4), missing green channels at the white locations can be estimated using the equation as follows:

$$\check{g}_{i,j} = W_{i,j} + \Delta C'_{g,w,(i,j)} \quad (9)$$

Combining the Eqs. (4), (7) and (9), we can acquire the equations of initially interpolated green channel at white pixel location (i, j) as follows:

$$\left\{ \begin{aligned} \check{g}_{i,j}^{D1} &= W_{i,j} + \frac{G_{i-1,j+1} - \tilde{w}_{i-1,j+1}}{4} + \frac{\tilde{g}_{i,j}^{D1} - W_{i,j}}{2} \\ &\quad + \frac{G_{i+1,j-1} - \tilde{w}_{i+1,j-1}}{4}, \quad \text{if } E_{D(i,j)} = D1 \\ \check{g}_{i,j}^{D2} &= W_{i,j} + \frac{G_{i-1,j-1} - \tilde{w}_{i-1,j-1}}{4} + \frac{\tilde{g}_{i,j}^{D2} - W_{i,j}}{2} \\ &\quad + \frac{G_{i+1,j+1} - \tilde{w}_{i+1,j+1}}{4}, \quad \text{if } E_{D(i,j)} = D2 \end{aligned} \right. \quad (10)$$

In the final equations, Eq. (10), we do not apply any direction-adaptive weights yet. The performance of the interpolation has chance to be improved by avoiding zippering artifact when we apply the directional weights from the all directions: NE, NW, SE and SW. In order to build direction-adaptive weights, we utilize the fact that the two pixels located across a strong edge influence each other less. This fact indicates that the difference in edge strength will be large when the pixels are located across a strong edge. In other words, the pixels are inversely correlated; therefore, we build inverse weights for improving performance near edge structures. Finally, the equations for interpolating missing green channels at white pixel locations, $\check{g}_{i,j}$ can be modified using direction-adaptive weights as follows:

$$\begin{aligned} \check{g}_{i,j} &= W_{i,j} + \Delta \tilde{C}_{g,w,(i,j)} \\ &= W_{i,j} + (\check{g}_{i,j} - W_{i,j}) \times A + \\ &\quad \left\{ I_{NE}(G_{i+1,j-1} - \tilde{w}_{i+1,j-1}) + I_{NW}(G_{i-1,j-1} - \tilde{w}_{i-1,j-1}) + \right. \\ &\quad \left. I_{SW}(G_{i-1,j+1} - \tilde{w}_{i-1,j+1}) + I_{SE}(G_{i+1,j+1} - \tilde{w}_{i+1,j+1}) \right\} \\ &\quad \times \frac{(1-A)}{(I_{NE} + I_{NW} + I_{SW} + I_{SE})} \end{aligned} \quad (11)$$

where coefficient A denotes the contribution of interpolation at (i, j) . The green and the white channel estimators at white and green sample locations can be calculated by

$$\begin{aligned} \check{g}_{i,j} &= \frac{I_{NE}G_{i+1,j-1} + I_{NW}G_{i-1,j-1} + I_{SW}G_{i-1,j+1} + I_{SE}G_{i+1,j+1}}{(I_{NE} + I_{NW} + I_{SW} + I_{SE})} + \\ &\quad \frac{I_{NE}(W_{i,j} - W_{i+2,j-2}) + I_{NW}(W_{i,j} - W_{i-2,j-2}) + I_{SW}(W_{i,j} - W_{i-2,j+2}) + I_{SE}(W_{i,j} - W_{i+2,j+2})}{2 \times (I_{NE} + I_{NW} + I_{SW} + I_{SE})} \\ \check{w}_{i,j} &= \frac{I_{NE}W_{i+1,j-1} + I_{NW}W_{i-1,j-1} + I_{SW}W_{i-1,j+1} + I_{SE}W_{i+1,j+1}}{(I_{NE} + I_{NW} + I_{SW} + I_{SE})} + \\ &\quad \frac{I_{NE}(G_{i,j} - G_{i+2,j-2}) + I_{NW}(G_{i,j} - G_{i-2,j-2}) + I_{SW}(G_{i,j} - G_{i-2,j+2}) + I_{SE}(G_{i,j} - G_{i+2,j+2})}{2 \times (I_{NE} + I_{NW} + I_{SW} + I_{SE})} \end{aligned} \quad (12)$$

The direction-adaptive weights can be calculated as follows:

$$\begin{cases}
I_{NE} = K_{NW} \times K_{SW} \times K_{SE} \\
I_{NW} = K_{NE} \times K_{SW} \times K_{SE} \\
I_{SW} = K_{NE} \times K_{NW} \times K_{SE} \\
I_{SE} = K_{NE} \times K_{NW} \times K_{SW} \\
K_{NE} = |S_{i,j} - S_{i+1,j-1}| + |S_{i+1,j-1} - S_{i+2,j-2}| \\
K_{NW} = |S_{i,j} - S_{i-1,j-1}| + |S_{i-1,j-1} - S_{i-2,j-2}| \\
K_{SW} = |S_{i,j} - S_{i-1,j+1}| + |S_{i-1,j+1} - S_{i-2,j+2}| \\
K_{SE} = |S_{i,j} - S_{i+1,j+1}| + |S_{i+1,j+1} - S_{i+2,j+2}|
\end{cases} \quad (13)$$

The inversely correlated weight I_{NE} , for example, can be achieved by multiplying three temporal weights K_{NW} , K_{SW} and K_{SE} which have the difference directional subscripts from I_{NE} . The temporal weight K_x , can be calculated by adding edge strength differences over a local window within the corresponding directions. Using the final equations, Eqs. (11), (12) and (13), we can interpolate green channel at the white sample locations.

4. Simulation Results

The common way to evaluate the performance of the demosaicing methods uses test images which are made by removing specific color channels to form mosaiced pattern. It is reasonable way for Bayer case; however, in the case of W-RGB, we cannot build images having the W-RGB pattern from full-color image because it is impossible to expect exact white value which do not satisfy the equation $W_{i,j} = R_{i,j} + G_{i,j} + B_{i,j}$. Therefore, we use the real-life prototype digital camera having Bayer-like W-RGB CFA for capturing raw test images.

Measuring the quality of results from W-RGB is not a simple task because it is not easy to obtain ground-truth images for comparison; therefore, we downscale the original W-RGB mosaiced images which have the resolution of 2608×1960 to half size for acquiring Bayer patterned ground truth images which have the resolution of 1304×980 .

As mentioned at the end of the Sect. 2, researches of dealing with W-RGB are at the early stage until now; therefore, all conventional methods remain poorly understood because they proposed the method focus on the concept only. As a result, we can only compare the proposed method with the color separation method [3] using the Eq. (1) which only has complete equations.

In order to compare the performance, CPSNR, FSIM [10] and S-CIELAB color distance [11] were measured against ground truth images. For simulation, we set the contribution parameter A to 7/10 for avoiding edges to be strengthened too much. The objective results of the measuring CPSNRs, FSIMs and average S-CIELAB distances are shown in Table 1.

Figures 3 and 4 show the input mosaiced images having W-RGB pattern and enlarged regions of the results using Fig. 3 (d) for comparison.

The result of the proposed method is closer to the ground-truth than that of the conventional method.

In addition, using the result of the proposed method, full-color images can be acquired using the conventional

Table 1 Comparisons of results (Pattern transformation).

Measurement	Method	(a)	(b)	(c)	(d)
		CPSNR	[3]	32.4278	35.8762
	Proposed	38.2564	40.0021	39.2901	36.7781
FSIM	[3]	0.9798	0.9831	0.9838	0.9815
	Proposed	0.9902	0.9927	0.9919	0.9926
S-CIELAB distance	[3]	0.4545	0.1254	0.2586	1.2153
	Proposed	0.3367	0.0976	0.2133	0.8696

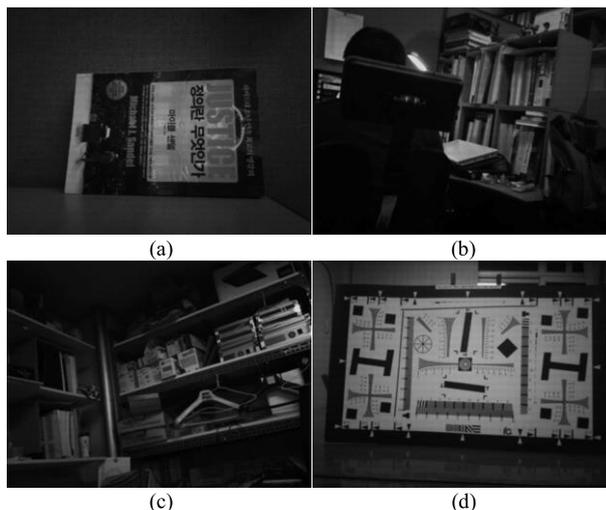


Fig. 3 The set of raw W-RGB mosaiced images for simulations from real-life prototype digital camera with W-RGB CFA.

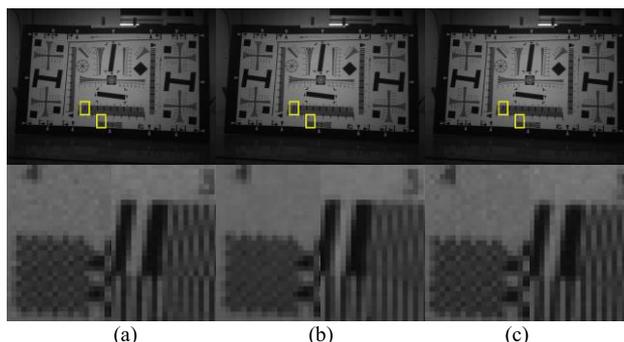


Fig. 4 Enlarged regions of the results using Fig. 3 (d) for comparison: (a) ground-truth, (b) conventional method and (c) proposed method

Table 2 Comparisons of results (Demosaic to full color).

Measurement	Method	(a)	(b)	(c)	(d)
		CPSNR	[3]	31.9487	35.2715
	Proposed	37.6189	39.6498	38.7568	36.0464
FSIM	[3]	0.9707	0.9829	0.9827	0.9798
	Proposed	0.9892	0.9911	0.9915	0.9901
S-CIELAB distance	[3]	0.4698	0.1277	0.2637	1.2362
	Proposed	0.3488	0.1014	0.2189	0.9545

Bayer demosaicing method. In this letter, Laplacian interpolation method is adopted for simple comparison and the results are shown in Fig. 5 and Table 2.

As we can see in the results from Fig. 4 and Table 1, the

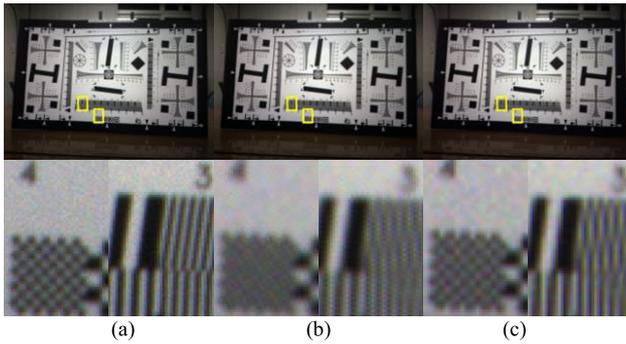


Fig. 5 The results of demosaicing (to full color) using Fig. 3 (d): (a) ground-truth, (b) conventional method and (c) proposed method

Table 3 Comparisons of computational cost.

Measurement	Method	(a)	(b)	(c)	(d)
		Processing time (s)	[7]	6.4479	7.4891
	[12]	9.1157	10.4650	9.6974	10.0237
	[13]	7.2677	6.1395	7.9689	7.3301
	Proposed	7.4175	8.7562	8.6611	9.0057

proposed method outperforms the conventional method in about +16.529% CPSNR, +0.998% FSIM, and +23.513% S-CIELAB error. Also, the full color images from the transformed Bayer mosaiced images which are generated by the proposed method is closer to the ground-truth than that of the conventional method as shown in Fig. 4 and Table 2.

Computational cost is also important in the field of CMOS image sensor. It is difficult to make detailed comparisons in computational cost of the proposed algorithm. The reason is that candidate methods for comparisons are hard to find because the other pattern transformation methods for Bayer-like W-RGB CFA do not exist at this point of time. For that, the processes of only one channel estimation of common Bayer algorithms are treated as comparing group. That is to say, parts of the common algorithms are used for rough comparison. We calculate processing time to evaluate the computational cost. We choose [7], [12] and [13] algorithm as comparing group, because they have similar methodologies for comparison. Calculations were performed on a MATLAB with 3.4 GHz CPU and 16 GB memory. The results are shown in Table 3.

Table 3 describes that the proposed method do not have the least complexity among those members of the comparing group. However, the proposed method does not seem to have immoderate complexity as the differences in the processing time among the results are not significant. Therefore, we can conclude that the proposed method outperforms the conventional methods in the estimation while it still bears an acceptable computational cost.

5. Conclusion

In this paper, we propose a new method of transforming Bayer-like W-RGB to Bayer pattern. The proposed method can be applied effectively to real-life situations based on the color difference assumption. With the proposed method, the images captured by a real-life digital camera with Bayer-like W-RGB CFA can be transformed to images with Bayer pattern with less blur and artifacts than conventional methods.

References

- [1] B.E. Bayer, "Color Imaging Array," U.S. Patent 3 971 065, July 1976.
- [2] Y. Egawa, N. Tanaka, N. Kawai, H. Seki, A. Nakao, H. Honda, Y. Iida, and A. Monoi, "A White-RGB CFA-Patterned CMOS Image Sensor with Wide Dynamic Range," Proc. IEEE Int. Conf. ISSCC, pp.52–595, Feb. 2008.
- [3] H. Honda, Y. Iida, G. Itoh, Y. Egawa, and H. Seki, "A novel Bayer-like WRGB color filter array for CMOS image sensors," Proc. SPIE Human Vision and Electronic Imaging XII, pp.64921J,1-10, Feb. 2007.
- [4] H. Honda, Y. Iida, and Y. Egawa, "High sensitivity color CMOS image sensor with WRGB color filter array and color separation process using edge detection," Proc. Int. Image Sensor Society Workshop, pp.263–266, 2007.
- [5] A. Getman, J. Kim, and T.C. Kim, "Imaging System having White-RGB Color Filter Array," Proc. IEEE Int. Conf. Image Processing, pp.569–572, Sept. 2010.
- [6] K. Shun, K. Rihito, and S. Shigetoshi, "Color Reproductivity Improvement with Additional Virtual Color Filters for WRGB Image Sensor," Proc. SPIE Color Imaging XVIII, 865205, Feb. 2013.
- [7] I. Pekkucuksen and Y. Altunbasak, "Edge Strength Filter Based Color Filter Array Interpolation," IEEE Trans. Image Process., vol.21, no.1, pp.393–397, Jan. 2012.
- [8] J. Wolberg, Data Analysis Using the Method of Least Squares: Extracting the Most Information from Experiments, pp.44–50, Springer, 2010.
- [9] J.E. Adams and J.F. Hamilton, "Adaptive color plane interpolation in single sensor color electronic camera," U.S. Patent 5 629 734, July 1997.
- [10] L. Zhang, D. Zhang, X. Mou, and D. Zhang, "FSIM: A Feature Similarity Index for Image Quality Assessment," IEEE Trans. Image Process., vol.20, no.8, pp.2378–2386, Aug. 2011.
- [11] G.M. Johnson and M.D. Fairchild, "Measuring images: differences, quality, and appearance," Proc. Conf. of SPIE/IS&T Electronic Imaging, pp.147–160, 2003.
- [12] K.-H. Chung and Y.-H. Chan, "Color Demosaicing Using Variance of Color Differences," IEEE Trans. Image Process., vol.15, no.10, pp.2944–2955, Oct. 2006.
- [13] D. Paliy, V. Katkovnik, R. Bilcu, S. Alenius, and K. Egiazarian, "Spatially adaptive color filter array interpolation for noiseless and noisy data," International Journal of Imaging Systems and Technology, vol.17, no.3, pp.105–122, 2007.