Cost-Effective Color Filter Array Demosaicing Using Spatial Correlation

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Abstract — *In this paper, we propose a cost-effective color filter array (CFA) demosaicing method for digital still cameras in which a single CCD or CMOS image sensor is used. Since a CFA is adopted, we must interpolate missing color values in the red, green and blue channels at each pixel location. While most state-of-the-art algorithms invest a great deal of computational effort in the enhancement of the reconstructed image to overcome the color artifacts, we focus on eliminating the color artifacts with low computational complexity. Using spatial correlation of the adjacent pixels, the edge-directional information of the neighbor pixels is used for determining the edge direction of the current pixel. We apply our method to the state-of-the-art algorithms which use edge-directed methods to interpolate the missing color channels. The experiment results show that the proposed method enhances the demosaiced image quality, especially visually, by removing most of the color artifacts*[1].

Index Terms — Bayer pattern, color filter array, demosaicing, spatial correlation

I. INTRODUCTION

Recently, digital still cameras that use charge coupled devices (CCD) or complementary metal oxide semiconductor (CMOS) image sensors have become popular. To make a color image, at least three color channels are required at each pixel location, but image sensors can perceive only the brightness of a pixel. Therefore, a digital still camera would need three separate sensors to completely measure each color channel. To acquire those three color channels, color filters having different spectral transmittances can be used for each sensor. Precise registration is then required to align the three channels.

To reduce the cost and complexity, digital still cameras adopt a single CCD/CMOS image sensor with a color filter array (CFA) to capture all three color channels at the same time. The Bayer pattern [1], shown in Fig. 1, is widely used as a CFA and provides the array or mosaic of the RGB colors. Since each pixel captures only one color channel, two other colors must be interpolated from the neighboring pixel values. This process is called CFA interpolation, or demosaicing. If this process is carried out inappropriately, the image suffers from various color artifacts, resulting in degraded color resolution. Therefore, an efficient demosaicing algorithm is required to overcome this physical limitation of the image sensors.

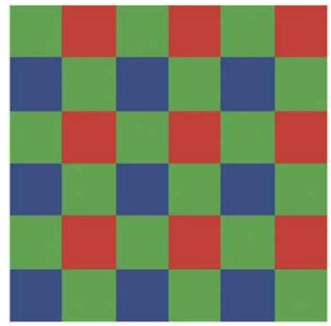

Fig. 1. Bayer CFA pattern

Many algorithms have been proposed over the last decade. These algorithms are broadly divided into four categories. In the first category, simple non-adaptive algorithms such as nearest neighbor, bilinear, or cubic interpolation are used to interpolate the missing pixel values [2]. They perform interpolation in a fixed pattern for every pixel. Even though they are computationally efficient, they introduce large errors in the edge region that blur the resulting image, because they do not consider the presence of object boundaries and indiscriminately combine color values across edges.

The second category of algorithms exploits the cross correlation between the color channels [3-6]. They assume that the hue of an image does not change abruptly between neighboring pixel locations. As a first step, these algorithms interpolate the luminance (green) channel, which is usually done using bilinear interpolation. The chrominance channels (red and blue) are estimated from the bilinearly interpolated "red hue" (red-to-green ratio) and "blue hue" (blue-to-green ratio). To be more explicit, the interpolated "red hue" and "blue hue" values are multiplied by the green channel to determine the missing red and blue channels at a particular pixel location. However, these algorithms also suffer from color artifacts, because the assumption of constant hue may not hold around certain kinds of edges.

The third category of algorithms is edge-directed interpolation [7-12]. These algorithms can detect local spatial features present in the pixel neighborhood, and then make effective choices as to which predictor to use for that neighborhood. In [9], it first defines two gradients, one in the horizontal direction and the other in the vertical direction, for each blue/red pixel location. If the horizontal gradient is greater and the vertical gradient is less than a predetermined threshold, suggesting a possible edge in the horizontal

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direction, interpolation for the green channel is performed along the vertical direction. If the vertical gradient is larger and the horizontal gradient is less than the threshold, interpolation is performed along the horizontal direction. When these two gradients are nearly equal, the green channel is obtained by averaging its four neighbors. Interpolation of the red and blue channels can be done by either interpolating color ratios (as in the second category of algorithms) or by interpolating the color differences instead of the color ratios. These algorithms usually have good quality even on the edge region. However, they still yield poor results in certain problematic regions of the images.

The fourth category of algorithms is post processing [13-18]. They start with an initial estimation of the original images, after which a correction procedure is applied. This procedure is intended to eliminate most of the color artifacts caused by the initial interpolation scheme. Despite the good quality obtained by this class of algorithms, there are still several typical artifacts that cannot be completely eliminated by them, no matter how sophisticated the correction method is. The reason is that the initial estimation typically gives rise to many color artifacts, which are difficult to compensate for using a computationally efficient algorithm. Moreover, a poor initial interpolation of the original image may threaten the stability of the entire algorithm, especially the iterative algorithms. In addition, the computational complexity is also a problem of this category.

Although color artifacts have been reduced by utilizing the mentioned computationally complex algorithms, color artifacts still remained along the edges and in the high frequency region of the image. Therefore, an efficient algorithm that can remove the color artifacts and has low computational complexity is required. In this paper, we propose a cost-effective CFA demosaicing method using the property of the spatial correlation. The edge-directional information of neighbor pixels is used to decide the edge direction of the current pixel.

This paper is organized as follows. Section II presents some conventional edge-directed demosaicing methods. A detail explanation for the proposed method is presented in section III. Section IV states experimental performance results and a comparison with other methods. The conclusions reached are discussed in section V.

II. CONVENTIONAL DEMOSAICING METHODS

In this section, we briefly review three conventional methods that we apply to our method: the edge-adaptive interpolation method [9], adaptive color plane interpolation method [11], and iterative interpolation method [18]. All these methods use the edge-directional information for interpolation. The interpolation direction is chosen to avoid interpolating across edges, instead the method allows interpolating along any edges in the image.

B	G	B_1	G	B
G	R_2	G_3	R_4	G
B_5	G_6	B_7	G_8	B_9
G	R_{10}	G_{11}	R_{12}	G
B	G	B_{13}	G	B

Fig. 2. Reference Bayer CFA pattern

A. Edge-adaptive Interpolation

This method interpolates the missing channels according to the edge pattern of the image. To make use of the edge information, the features in the edge region have to be studied. Interpolation is performed only along the edge direction that has a lower gradient than the other direction. Referring to Fig. 2, horizontal and vertical gradients at a missing green pixel location can be calculated from the adjacent green pixels using

$$\begin{aligned} DH &= \left|G_6 - G_8\right| \\ DV &= \left|G_3 - G_{11}\right| \end{aligned} \tag{1}$$

The missing green channel *G7* can be estimated as

$$G_7 = \begin{cases} \dfrac{G_6 + G_8}{2} & if\ DH < DV \\ \dfrac{G_3 + G_{11}}{2} & if\ DH > DV \\ \dfrac{G_3 + G_6 + G_8 + G_{11}}{4} & if\ DH = DV \end{cases} \tag{2}$$

Interpolation of red and blue channels can be performed by the first or the second categories of algorithms.

B. Adaptive Color Plane Interpolation

In [11], they begin by using edge-directed interpolation for the green channel. Correction terms from the red and blue channels are added to this initial estimate. They compute the gradient for the red or blue channels along the interpolation row or column and use this to correct the simple averaging interpolation. This correction term reduces aliasing passed to the output by the simple averaging filter.

Referring to Fig. 2, horizontal and vertical gradients are defined as

$$\begin{aligned} DH &= \left|-B_5 + 2B_7 - B_9\right| + \left|G_6 - G_8\right| \\ DV &= \left|-B_1 + 2B_7 - B_{13}\right| + \left|G_3 - G_{11}\right| \end{aligned} \tag{3}$$

These gradients are composed of second derivative terms for the chromaticity channel and gradients for the luminance data. As such, these gradients sense the high spatial frequency information in the pixel neighborhood in the horizontal and vertical directions.

The missing green pixel *G7* can be estimated as

$$G_7 = \begin{cases} \dfrac{G_6 + G_8}{2} + \dfrac{-B_5 + 2B_7 - B_9}{2} & if\ DH < DV \\ \dfrac{G_3 + G_{11}}{2} + \dfrac{-B_1 + 2B_7 - B_{13}}{2} & if\ DH > DV \\ \dfrac{G_3 + G_6 + G_8 + G_{11}}{4} & \\ + \dfrac{-B_1 - B_5 + 4B_7 - B_9 - B_{13}}{8} & if\ DH = DV \end{cases} \tag{4}$$

These predictors are composed of arithmetic averages for the green channel and appropriately scaled second derivative terms for the chromaticity channel. This comprises the first pass of the interpolation algorithm. The second pass involves populating the chromaticity channels.

The interpolation of red and blue channels uses diagonal gradients to determine the edge direction instead of horizontal and vertical gradients. The estimates of the missing color channels are similar to green channels interpolation. They are composed of arithmetic averages for the chromaticity channel and appropriately scaled second derivative terms for the green channel.

C. *Iterative Interpolation*

In [18], a coarse approximation of color places is first obtained by intraplane interpolation techniques, such as bilinear, edge-adaptive interpolation or adaptive color plane interpolation. To reduce the color artifacts, each channel is updated. To update the initially interpolated image, two color difference signals are defined as

$$D_R = R - G, D_B = B - G \tag{5}$$

Referring to Fig. 2, *G7* at the location of *B7* is updated by

$$\hat{D}^n_{B7} = \frac{D^n_{B3} + D^n_{B6} + D^n_{B8} + D^n_{B11}}{4} \tag{6}$$

$$G^{n+1}_{B7} = B^n_7 - \hat{D}^n_{B7} \tag{7}$$

where $\hat{D}^n_{B7}$ is an updated color difference and n denotes the iteration index. The processing of the green pixel at the location of the red pixel is similar. The red pixels are updated in two steps. Referring to Fig. 2, *R6* at the location of *G6* is updated by

$$\hat{D}^n_{R6} = \frac{D^n_{R2} + D^n_{R10}}{2} \tag{8}$$

$$R^{n+1}_6 = G^n_6 + \hat{D}^n_{R6} \tag{9}$$

and *R7* at the location of *B7* is updated by

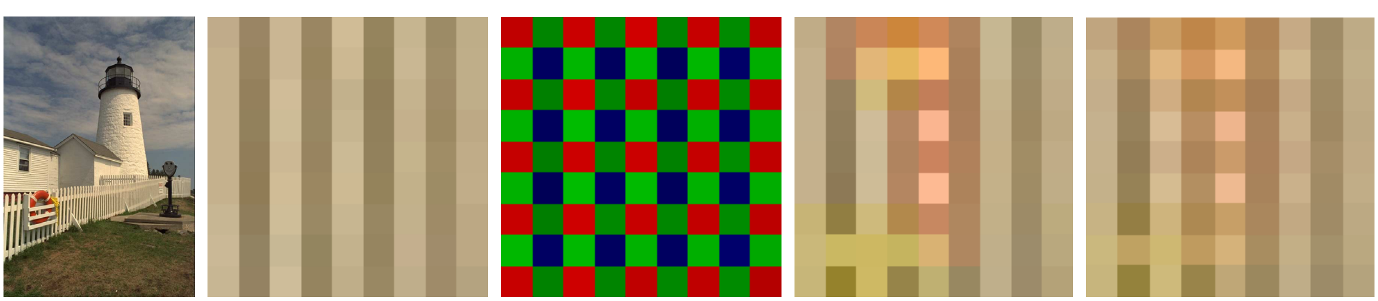
$$\hat{D}^n_{R7} = \frac{D^n_{R2} + D^n_{R4} + D^n_{R10} + D^n_{R12}}{4} \tag{10}$$

$$R^{n+1}_7 = G^n_7 + \hat{D}^n_{R7} \tag{11}$$

The treatment of blue pixels is similar to that of red pixels. The iteration is performed until the stopping criterion is satisfied.

III. The Proposed Demosaicing Method

To minimize the color artifacts, most methods interpolate along the edge and use cross correlation. It works well as long as it is able to calculate the edge direction for the green channel correctly, since it interpolates the green channel first and then interpolates red/blue channels using the interpolated green channel. However, it fails to determine exact directions in some regions if vertical gradient and horizontal gradient are similar. If the interpolation is performed along the vertical direction in the horizontal region, it causes severe color artifacts. Fig. 3 illustrates the color artifacts generated by the ambiguous regions, where it is difficult to determine the edge direction. Fig. 3(a) is the original image (lighthouse) and



(a) (b) (c) (d) (e)

Fig. 3. Examples to illustrate the color artifacts generated by the ambiguous regions.: (a) lighthouse, (b) zoomed part of fence region in lighthouse image, (c) the mosaic image from (b), (d) demosaiced image by [11], (e) Demosaiced image by [18].

Fig. 3(b) is a zoomed part of fence region in Fig. 3(a). It is easy to see the sharp transition between the bright white patch in the fence and the dark background. Fig. 3(c) is a mosaic image produced from Fig. 3(b), and it is not clear whether the missing green pixel values should be interpolated using vertical or horizontal neighbors. Fig. 3(d) and Fig. 3(e) are demosaiced images using the methods [11] and [18], respectively. In Fig. 3(d) and Fig. 3(e), color artifacts still exist even though the iterative interpolation method [18] is used, since the color artifacts of the initial interpolation step are too severe to eliminate using the post processing.

To interpolate the missing color channels without color artifacts, larger regions with more complex predictors can be used to be determine the edge direction of the pixels exactly. However, it increases the computational complexity and requires additional memories.

Instead of using a large window, we use the spatial correlation of the adjacent pixels. Image spatial correlation refers to the fact that within a homogeneous image region, neighboring pixels are similar. Therefore, adjacent pixels at the edge region would have the same edge direction. Fig. 4 shows examples. Along the horizontal (H) or vertical (V) edge, the direction of the adjacent pixels is the same. Therefore, we can use the directional information of neighbor pixels to determine the direction of the current pixel.

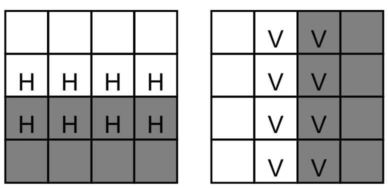


Fig. 4. Examples of the spatial correlation between the adjacent pixels

The proposed method is applied to the green channel interpolation. Since the green channel is sampled at a rate twice as high as the red and blue channels and red and blue channels are interpolated using the green channel in most methods, the quality of the interpolated green channel is very important to minimize the color artifacts. Edge-directional information of the current pixel ($d_{i,j}$) is defined as

$$d_{i,j} = \begin{cases} 1 & \text{if } DH < DV \\ -1 & \text{if } DH > DV \\ 0 & \text{if } DH = DV \end{cases} \tag{12}$$

$d_{i,j}$ is set to 1 if the direction of the pixel is horizontal, and set to -1 if the direction of the pixel is vertical. If the vertical and horizontal directions have the same gradient value, then it is set to 0. Using (12), new horizontal (DH') and vertical (DV') gradients are defined as

$$\begin{aligned} DH' &= DH - w \cdot d_{i,j-2} \\ DV' &= DV + w \cdot d_{i-2,j} \end{aligned} \tag{13}$$

where w is weight, $d_{i,j-2}$ is directional information of the left green channel, $d_{i-2,j}$ is directional information of the upper green channel. DH and DV are the gradient calculated by any kinds of edge-adaptive methods. Compared to the conventional methods, edge-directional information of neighbor pixels is simply added with weight.

If $d_{i,j-2}$ is 1, it means that the direction of the left green pixel is horizontal, then DH' decreases. Decreasing DH' means that the direction of the pixel will be regarded as a horizontal edge with high possibility. If $d_{i,j-2}$ is -1, it means that the direction of the left green pixel is vertical, then DH' increases. Therefore, the pixel will be less likely to interpolate along the horizontal direction. In the case of $d_{i,j-2}$ is 0, it does not affect the decision of the direction of the current pixel.

Red and blue channels are interpolated using the conventional methods. Since green channels are interpolated more accurately, the interpolation results of red and blue channels are also enhanced.

With these simple directional terms, most visible color artifacts can be eliminated. The proposed method can be applied to any conventional edge-adaptive interpolation methods, and only two additions are added to the conventional methods. The conventional demosaicing methods with high quality usually use the iteration method to eliminate the color artifacts. However, these iteration methods are not suitable for the real-time hardware implementation. In addition to that, the color artifacts are not completely removed even using these iteration methods. Therefore, the proposed method is very useful, since it can be directly implemented into the hardware and it can eliminate most visible color artifacts.

IV. EXPERIMENTAL RESULTS

The proposed method was tested using the color test images (768 x 512) shown in Fig. 5. The proposed method was applied to the three demosaicing methods which were presented in section II.

Fig. 5. Color images used in the experiments

The mean squared error (MSE), peak signal to noise ratio (PSNR), and normalized color difference (NCD) [19] were used in order to measure the performance of the proposed algorithms. The PSNR is defined in decibels as

$$PSNR = 10\log_{10}\frac{255^2 \cdot N}{\|x - x'\|^2} \tag{14}$$

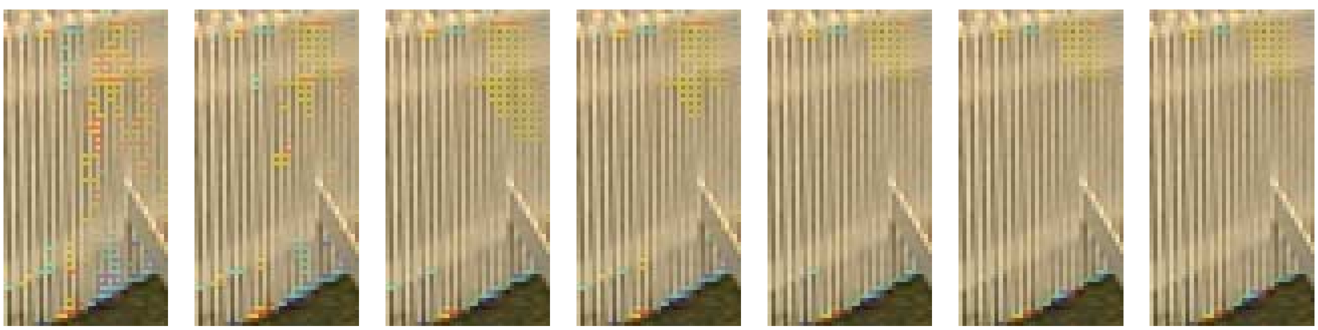
where N is the total number of pixels in the image, x is the original image, and x' is the interpolated image. The NCD is computed in the L^*a^*b color space by using the following equation

$$NCD = \frac{\sum_{i=1}^{K_1}\sum_{j=1}^{K_2}\|\Delta E_{Lab}\|}{\sum_{i=1}^{K_1}\sum_{j=1}^{K_2}\|E^*_{Lab}\|} \tag{15}$$

where K_1 and K_2 are the image width and height, and ΔE_{Lab} is the perceptual color error between two color vectors, which is defined as the Euclidean distance between them, and is given by

$$\Delta E_{Lab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \tag{16}$$

where ΔL^*, Δa^*, and Δb^* are the differences in the L^*, a^*, and b^{**} components. The magnitude of the pixel vector in the $L^*a^*b^*$ of the original image is E^*_{Lab} and is given by

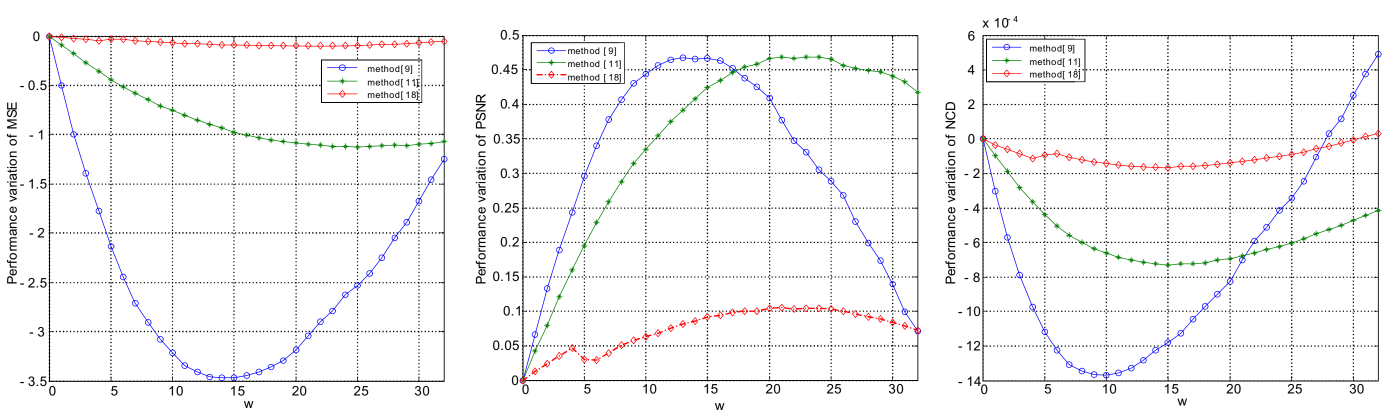


(a) (b) (c) (d) (e) (f) (g)

Fig. 6. Enlarged parts of the demosaiced lighthouse image by method [11] corresponding to (a) w=0, (b) w=5, (c) w=10, (d) w=15, (e) w=20, (f) w=25, (g) w=30

(a) (b) (c) (d) (e) (f) (g)

Fig. 7. Enlarged parts of the demosaiced lighthouse image by method [11] corresponding to (a) w=0, (b) w=5, (c) w=10, (d) w=15, (e) w=20, (f) w=25, (g) w=30



(a) (b) (c)

Fig. 8. The averaged performance variations of the proposed method depending on w related to the images in Fig. 5. (a) MSE, (b) PSNR, (c) NCD

TABLE I. AVERAGED PERFORMANCE COMPARISON RELATED TO THE COLOR IMAGES SHOWN IN FIG. 5

		CONVENTIONAL			PROPOSED		
	CHANNEL	MSE	PSNR	NCD(x10^-2)	MSE	PSNR	NCD(x10^-2)
METHOD [9]	R	42.61	33.02		38.68	33.50	
	G	40.85	33.32	3.491	37.39	33.79	3.373
	B	44.70	32.86		40.82	33.33	
METHOD [11]	R	18.54	36.45		17.44	36.79	
	G	13.09	38.25	2.500	12.12	38.67	2.427
	B	19.92	36.27		18.81	36.59	
METHOD [18]	R	11.39	37.44		11.27	37.48	
	G	5.10	41.04	2.035	5.01	41.13	2.018
	B	11.42	37.82		11.33	37.88	

TABLE II. THE PERFORMANCE COMPARISON OF THE LIGHTHOUSE IMAGE

		CONVENTIONAL			PROPOSED		
	CHANNEL	MSE	PSNR	NCD(x10^-2)	MSE	PSNR	NCD(x10^-2)
METHOD [9]	R	31.86	33.04		26.15	33.88	
	G	29.91	33.35	3.133	24.78	34.16	2.991
	B	31.75	33.10		25.62	34.02	
METHOD [11]	R	14.13	36.42		13.25	36.69	
	G	9.67	38.16	2.289	8.89	38.52	2.241
	B	12.88	36.93		12.09	37.20	
METHOD [18]	R	8.86	38.17		8.40	38.38	
	G	3.69	41.74	1.736	3.51	41.92	1.719
	B	7.27	38.67		6.74	38.94	

$$E^*_{Lab} = [(L^*)^2 + (a^*)^2 + (b^*)^2]^{1/2} \tag{17}$$

The evaluation of the weight w is introduced in Fig. 6 and Fig 7. Based on method [11], the proposed method was applied. Fig. 6(a) and Fig. 7(a) show the demosaiced when w is 0, which is the result of method [11].

Many color artifacts are shown in Fig. 6(a) where the high frequency region is. Fig. 6(b)-(g) shows the mitigation of the effect by increasing w of (13). If w is larger than 20, most color artifacts are removed, and the effect of w is saturated. However, if w is larger than 15, some side effects are observed in Fig. 7. In Fig. 7, most regions are smooth and there is a certain vertical edge in the middle of the image, which is a window frame. In Fig. 7(b)-(d), there is no performance degradation. However, in Fig. 7(e)-(g), new color artifacts are shown, because the large w can cause wrong decisions for edge direction. Fig. 8 shows the averaged performance variations of the proposed method depending on w ranging from 0 to 32 with a fixed step of $\Delta w = 1$. The performance difference between the proposed method and the conventional method is plotted depending on w by subtracting the performance of the conventional method from that of the proposed method. The MSE, PSNR and NCD are set to 0 when w=0, which corresponds to the conventional methods. The green channel was used to measure MSE and PSNR. Experimental results with a wide set of the images shows that the increase of w eliminates color artifacts in high frequency image transitions. The weight w=15 usually produces desirable and robust performance, so all subsequent experimental results presented in this paper have been obtained using w = 15.

Table I and II show the numerical results with the proposed method and without the proposed method. Table I compares the averaged results of MSE and PSNR of each R, G and B channel, and NCD related to the test images in Fig. 5. The MSE decreases by 0.09 to 3.93, the PSNR improved from 0.09dB to 0.48dB. The NCD also decreases by 0.17×10^{-3} to 1.18×10^{-3}. Table II summarizes the comparison results of the lighthouse image. The MSE decreases by 0.18 to 6.13, the PSNR improved by 0.18dB to 0.92dB. The NCD also decreases by 0.17×10^{-3} to 1.42×10^{-3}. Using the proposed method, the performance increases slightly, since the proposed method affects only ambiguous regions like the fence of the lighthouse. These improvements are visually focused on the lighthouse image, which has several challenging regions of which it is difficult to determine the exact direction. Fig. 9 and Fig. 10 show the demosaicing results by using the conventional methods with and without the proposed method. Fig. 9 shows the results of interpolating the fence region of the lighthouse, which has fine detailed regions. Color artifacts are shown of all images demosaiced using the conventional method, especially in the simple edge-adaptive interpolation method. We can find that demosaiced images, which the proposed method is applied to, show less color artifacts, since the edge-direction is determined correctly. Similar results are shown in Fig. 10. Almost all color artifacts are eliminated by applying the proposed method.

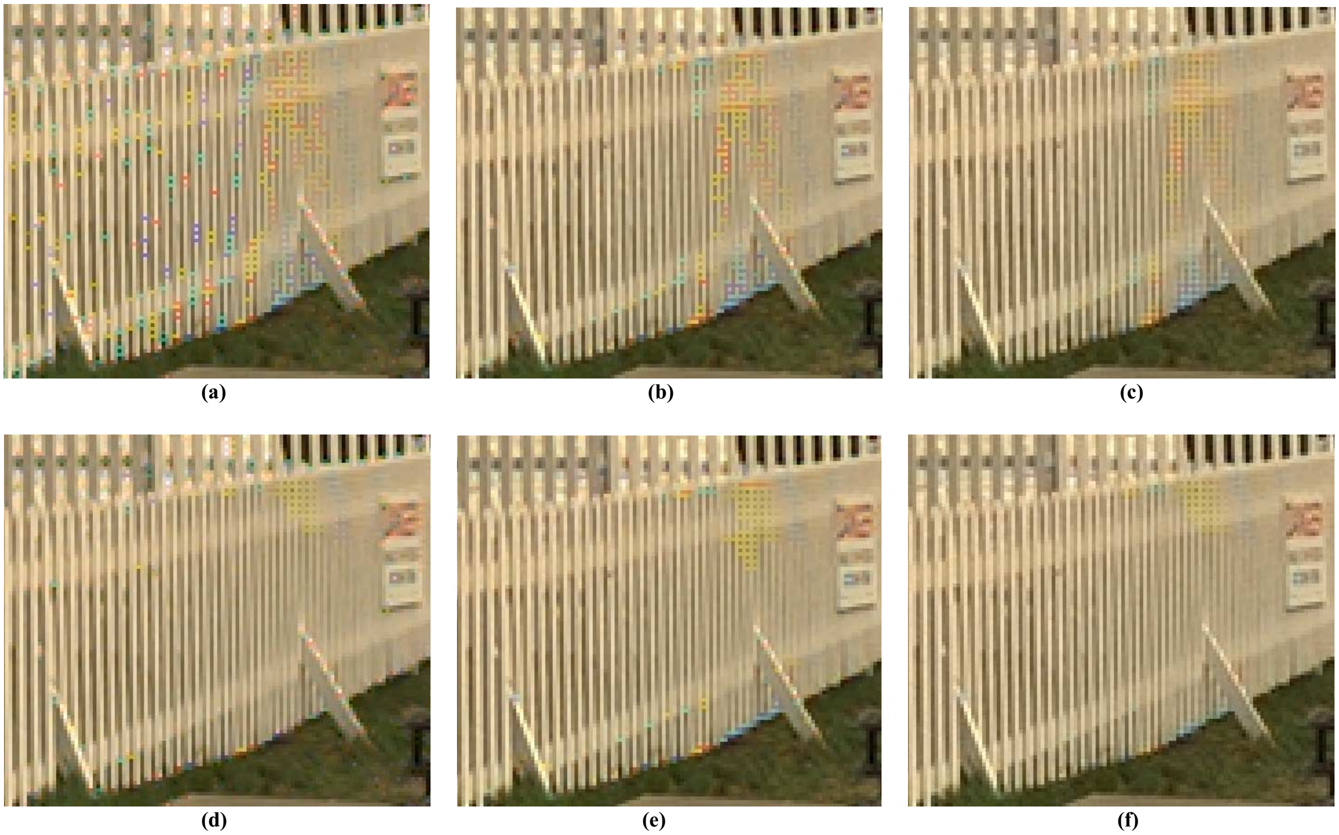


Fig.9. The fence region of the lighthouse image: (a) method [9], (b) method [11], (c) method [18], (d) method [9] with the proposed method, (e) method [11] with the proposed method, and (f) method [18] with the proposed method

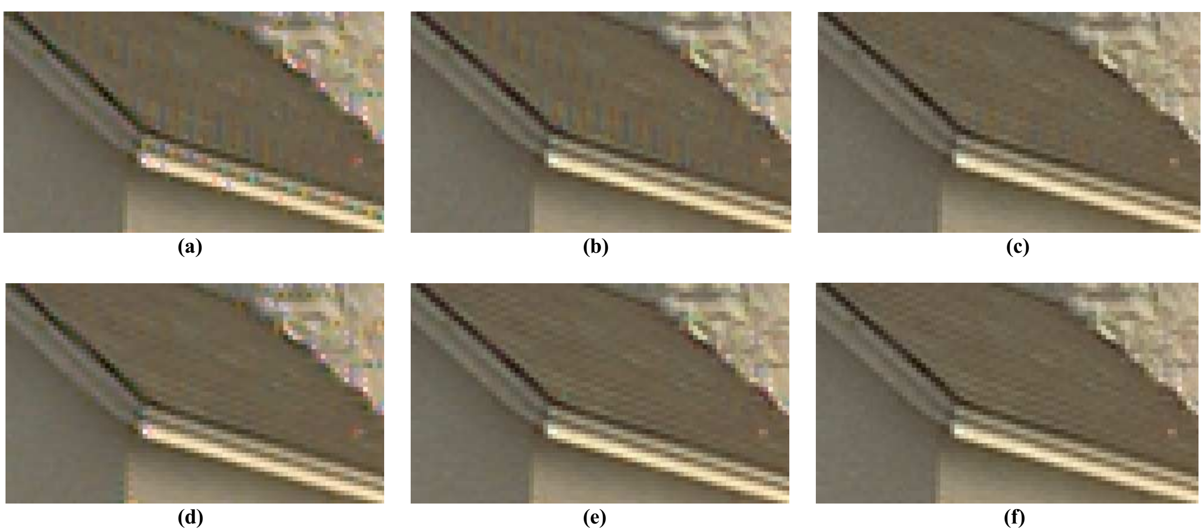


Fig.10. The roof region of the lighthouse image: (a) method [9], (b) method [11], (c) method [18], (d) method [9] with the proposed method, (e) method [11] with the proposed method, and (f) method [18] with the proposed method

V. CONCLUSION

A cost-effective demosaicing method using spatial correlation was proposed in this paper. We used the edge-directional information of neighbor pixels for determining the edge direction of the current pixel to reduce the visual color artifacts. The proposed method could be applied to any demosaicing methods that interpolate the missing color channels edge-adaptively. In addition, additional complex computations were not required, and only two additions were needed to estimate new vertical and horizontal gradients. Therefore, it is very useful for a real-time image signal processor for a single CCD/CMOS image sensor. The experimental results also showed that the proposed method improved upon the conventional methods, especially visually, by removing the most color artifacts.

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