https://doi.org/10.2352/ISSN.2470-1173.2017.13.IPAS-085

Color Interpolation Based on Colorization for RGB-White Color Filter Array

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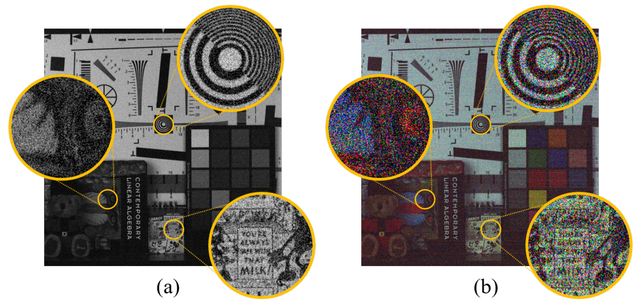
Abstract

Recently, RGB-White(RGBW) sensors have been developed to take advantages of high-sensitive white(W) channel. Especially in the low light condition, the W channel has better SNR (Signal to Noise Ratio) characteristics than other color channels. In this paper, a new color interpolation method for the RGBW sensor is proposed. To make the best use of the high-sensitive W channel, we use a random pattern RGBW Color Filter Array(CFA). The most of pixels in the CFA sample the W channel values, when a small number of pixels sample the R, G, and B channel values respectively. At the initial step, missing W channel values in positions of pixels which sample the R, G, and B channel are estimated by edge adaptive scheme. After that, the color difference channels, i.e., R-W, G-W, and B-W, are estimated by the scheme of colorization. Experimental results show that the proposed algorithm performs better than the results from Bayer CFA in terms of SNR and object discrimination.

Introduction

To obtain full color images, many of digital imagers have used a single sensor based system. Digital imagers could reduce the cost and size by using a single sensor. However, photodiodes in a single sensor, such as CCD (Charged Coupled Device) or CMOS (Complementary Metal Oxide Semiconductor), can only count the number of photons, not discriminate the energy of photons. To discriminate the energy which means the color of photons, the surface of each pixels is covered by a color filter which selects the spectrum of received photons. As a result, each pixel captures the one of the primary colors, i.e. red, green, and blue. Bayer CFA [1] is the most popular CFA, which is composed of 50% of green, 25% of red, and 25% of blue pixels. To obtain more sensitive image in the low light condition, some manufacturers have produced CFA patterns which include panchromatic W pixels [2, 3]. As a W pixel responds to all the spectrum of visual band, it receives more photons than the other color pixels at the same time. As a result, it is possible to get the high SNR-image due to the W pixels. Numerous demosaicing algorithms [6–12] have been developed for Bayer CFA pattern up to present, so that the manufacturers usually convert a RGBW sampled image to a RGB (Bayer pattern) sampled image. This process may overlap demosaicing artifacts such as an aliasing problem and lead to the color distortion. Therefore, a direct demosaicing algorithm which is optimized to a RGBW CFA is necessary.

The purpose of the colorization based RGBW sensor is to maximize the use of high-SNR white channel when the RGB channels are reconstructed. Figure 1 shows that the panchromatic white channel has more spatial information and less noise comparing with the RGB channel when the both images are captured in the same low light condition. In the colorization method,



(a) (b)

Figure 1. *(a) W channel and (b) RGB channel images in the low light condition(1lux)*

a color image is estimated from a monochrome image with a few number of color seeds, namely representative pixels, which contain the chrominance information. Levin et al.[5] proposed the colorization process which is formulated into an optimization problem. The colorization technique brought about the idea that the R, G, and B channels can be reconstructed by a small number of color seeds which contain original color information, and the full-resolution W channel. On account of the colorization technique, it is possible to estimate the color channels, i.e., R, G, and B, with a noise level of the W pixel, even though color seeds have relatively low-SNR characteristics in the extremely low light condition.

Related works

To explain the proposed method, it is necessary to understand Levin's colorization technique. It starts with the fact that neighbouring pixels which have similar values of luminance channel are likely to have similar values of chrominance channel. For this reason, it is possible to reconstruct the color image from the monochrome luminance image, using a few number of the representative pixels which contain chrominance information. When the RGB color image is converted to the YCbCr image, the cost function of Levin's colorization method can be expressed as follow:

$$\underset{\mathbf{u}}{\operatorname{argmin}} J(\mathbf{u}) = \|\mathbf{x} - \mathbf{A}\mathbf{u}\|^2, \tag{1}$$

where $\mathbf{x}$ is a sparse vector which contains the chrominance values only at the positions of the representative pixels and zeros at all the other positions, and $\mathbf{u}$ is a vector which means the chrominance channel to be solved. The matrix $\mathbf{A}$ is defined as $\mathbf{A} = \mathbf{I} - \mathbf{W}$, where $\mathbf{I}$ is an identity matrix, and the weight matrix $\mathbf{W}$ is composed of weighting components ω'_{rs} defined as

$$\omega'_{rs} = \begin{cases} 0 & \text{if } r \in \Omega \\ \omega_{rs} & \text{otherwise,} \end{cases} \tag{2}$$

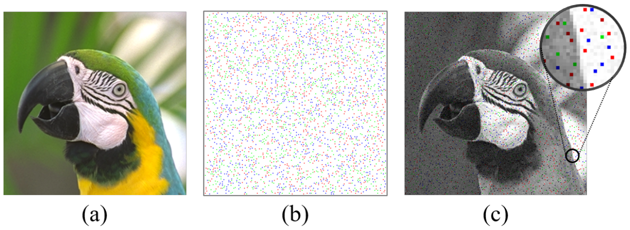


Figure 2. (a) Original image, (b) randomly sampled RGBW CFA pattern, (c) sampled image using (b) pattern from (a).

where

$$\omega_{rs} \propto e^{-(\mathbf{y}(r)-\mathbf{y}(s))^2/2\sigma_r^2}. \tag{3}$$

Ω is the set of the representative pixels, ω_{rs} is the weight between the luminance pixels $\mathbf{y}(r)$ and $\mathbf{y}(s)$, and σ_r is a deviation of in the 8-neighbourhood pixels of $\mathbf{y}(r)$. Therefore, the chrominance channel $\mathbf{u}$ can be solved by minimizing the cost function defined in (1) as follow:

$$\mathbf{u} = \mathbf{A}^{-1}\mathbf{x}. \tag{4}$$

As proven in previous works at [5], $\mathbf{A}$ is invertible, and can vary for different sets of representative pixels.

Proposed Method

Randomly sampled RGBW CFA pattern

In Bayer CFA pattern, the G channel contains twice as many pixels as the R or B channel. For the spectral band of the G channel is between those of the R and B channel, the G channel has relatively high spectral correlation with both R and B channel. Furthermore, the G channel is highly related with the luminance of the image which has a lot of influence on the perceptual quality of the color image. For those reason, it is advantageous that the G channel possesses the half of the pixels of the CFA pattern.

While the spectral band of the G channel is one of the narrow band of the visible band, the W channel receives whole range of the visible band. Thus, the W channel has higher spectral correlation with the R or B channel comparing with the G channel, where the G and W channels are also greatly correlated. Besides, the W channel can be regarded as the luminance channel, consequently, it is adequate to use the W channel as the major channel of the CFA pattern. In addition, especially in the low light condition, the SNR of the W channel is much higher than those of other primary color channels.

This article describes the imaging system which focuses on the extremely low light condition, so that a CFA pattern is needed to maximize the above merits of the panchromatic W channel. To obtain a high-sensitive image in the low light condition, a CFA pattern is designed as a small number of the R, G, and B pixels are sampled in the random positions, while the rest of pixels receive the panchromatic W channel. Figure 2 explains how the R, G, B, and W channels are sampled in the captured image of the proposed RGBW CFA pattern. The proportions of the R, G, and B channels in the proposed RGBW CFA pattern are equal. As shown in Fig. 2(b), the white pixels designate the pixels which capture panchromatic W channel information. Likewise, the red, green, and blue pixels in Fig. 2(b) designate the pixels which capture the R, G, and B channel information.

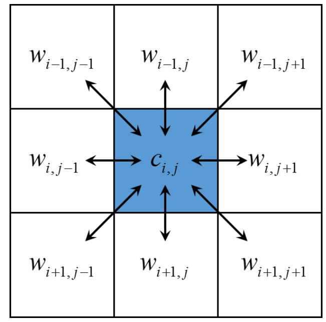


Figure 3. A 3×3 window where W channel of the central pixel is to be estimated.

W channel Interpolation

In the most of color interpolation methods for Bayer CFA pattern, the G channel is interpolated at first, because the G channel possesses most spatial information of the CFA sampled image. Then the G channel assists the subsequent R and B channel interpolation by making full and direct use of the spectral correlation. As discribed previous subsection, the W channel which possesses the majority of the pixels in the RGBW CFA pattern is spectrally correlated with the R, G, and B channel, so it is appropriate to assist the R, G, and B interpolation. Therefore, as a initial step to reconstruct the color image from the proposed RGBW CFA patterned image, the W channel is interpolated in positions of the R, G, and B pixels. Figure 3 shows a 3×3 window of the RGBW CFA samples, where w denotes the W channel, c denotes one of the primary color channel, i.e., $c \in \{r, g, b\}$. When i and j denote the row and column indice of the location of the missing W pixel, it can be estimated from the 8 neighborhood W channel values as follow:

$$\hat{w}_{i,j} = \frac{\sum_{u,v \in \mathcal{N}(i,j)} \alpha_{u,v} w_{u,v}}{\sum_{u,v \in \mathcal{N}(i,j)} \alpha_{u,v}}, \tag{5}$$

where $\mathcal{N}(i,j)$ denotes the set of the 8 neighborhood of $\{i,j\}$, and the directional weight $\alpha_{u,v}$ is derived in (6).

RGB channel Interpolation

After the W channel is fully interpolated, the RGB channels are interpolated by using a colorization scheme. As described above, the primary color channel pixels are rarely sampled and distributed randomly. In addition, the primary color channels are are more degraded in terms of the noise comparing with the W channel in the low light condition. Thus, a colorization matrix which is essential for the colorization process is designed to consider not only the diffusion of the original color seeds, but also the restoration of the color seeds from the noise.

Let $\mathbf{w}$ and $\mathbf{c}$ are the lexicographically ordered vectors to denotes the 2D images corresponding to w and c, for example, $\mathbf{w}$ can be expressed with w as

$$\mathbf{w} = [w_{1,1}, w_{2,1}, \cdots, w_{N_r,1}, w_{1,2}, \cdots, w_{1,N_c}, \cdots, w_{N_r,N_c}]^T. \tag{7}$$

For $\mathbf{c} \in \{\mathbf{r}, \mathbf{g}, \mathbf{b}\}$, the color difference channel between the primary color channel and the W channel can be defined as

$$\mathbf{u}_c = \mathbf{c} - \mathbf{w}. \tag{8}$$

$$
\begin{aligned}
\alpha_{i-1,j-1} &= \frac{1}{|c_{i,j}-w_{i-1,j-1}|+0.5|w_{i-1,j}-w_{i,j+1}|+0.5|w_{i,j-1}-w_{i+1,j}|}, & \alpha_{i+1,j+1} &= \frac{1}{|c_{i,j}-w_{i+1,j+1}|+0.5|w_{i-1,j}-w_{i,j+1}|+0.5|w_{i,j-1}-w_{i+1,j}|} \\
\alpha_{i-1,j+1} &= \frac{1}{|c_{i,j}-w_{i-1,j+1}|+0.5|w_{i-1,j}-w_{i,j-1}|+0.5|w_{i,j+1}-w_{i+1,j}|}, & \alpha_{i+1,j-1} &= \frac{1}{|c_{i,j}-w_{i+1,j-1}|+0.5|w_{i-1,j}-w_{i,j-1}|+0.5|w_{i,j+1}-w_{i+1,j}|} \\
\alpha_{i,j-1} &= \frac{1}{|c_{i,j}-w_{i,j-1}|+0.5|w_{i-1,j-1}-w_{i-1,j}|+0.5|w_{i+1,j-1}-w_{i+1,j}|}, & \alpha_{i,j+1} &= \frac{1}{|c_{i,j}-w_{i,j+1}|+0.5|w_{i-1,j+1}-w_{i-1,j}|+0.5|w_{i+1,j+1}-w_{i+1,j}|} \\
\alpha_{i-1,j} &= \frac{1}{|c_{i,j}-w_{i-1,j}|+0.5|w_{i-1,j-1}-w_{i,j-1}|+0.5|w_{i-1,j+1}-w_{i,j+1}|}, & \alpha_{i+1,j} &= \frac{1}{|c_{i,j}-w_{i+1,j}|+0.5|w_{i+1,j-1}-w_{i,j-1}|+0.5|w_{i+1,j+1}-w_{i,j+1}|}
\end{aligned}
\tag{6}
$$

Figure 4. *Kodak 24 test image set for PSNR evaluation.*

Here, $\mathbf{x}_c$ is a sparse vector which contains the color difference values only at the positions of the representative pixels and zeros at all the other positions as follow:

$$\mathbf{x}_c(n) = \begin{cases} \mathbf{c}(n) - \hat{\mathbf{w}}(n) & \text{if } n \in \Psi_c \\ 0 & \text{otherwise,} \end{cases} \tag{9}$$

where n is the position index of the pixel, and Ψ_c represents the set of the representative pixel positions of c channel. With the completely interpolated W channel, the cost function which diffuses the randomly sampled the primary color channels and suppresses the noise is expressed as

$$J(\mathbf{u}_c) = \|\mathbf{x}_c - \mathbf{A}_c\mathbf{u}_c\|^2, \tag{10}$$

where $\mathbf{A}_c = \mathbf{I} - \mathbf{W}_c$, $\mathbf{I}$ is an identity matrix, and $\mathbf{W}_c$ is a weight matrix which is composed of

$$\omega'_{rs} = \begin{cases} \eta\,\omega_{rs} & \text{if } r \in \Psi_c \\ \omega_{rs} & \text{otherwise,} \end{cases} \tag{11}$$

where $\omega_{rs} \propto e^{-(\mathbf{w}(r)-\mathbf{w}(s))^2/2\sigma_r^2}$, and η is a small value which suppresses the noise in the color seeds. Solving (10), therefore, $\mathbf{u}_c$ can be estimated as follow:

$$\hat{\mathbf{u}}_c = \mathbf{A}_c^{-1}\mathbf{x}_c. \tag{12}$$

Comparison of the PSNR(dB) values of the color interpolated kodak RGB images from Bayer CFA and the proposed RGBW CFA with different noise level

Data	15dB		20dB	
	Bayer	Proposed	Bayer	Proposed
1	15.9915	18.6566	20.6240	23.0903
2	16.7149	19.1721	21.0217	22.8157
3	16.1533	18.7328	20.7928	23.1957
4	16.2353	18.8607	20.7814	22.9375
5	16.4626	18.8432	20.9141	22.7977
6	16.2170	18.7777	20.8267	23.1453
7	15.9752	18.7681	20.7311	23.0287
8	16.2440	18.7045	20.7274	23.0009
9	15.8794	18.8375	20.6406	23.3527
10	15.8793	18.7442	20.6563	23.3860
11	16.1549	18.9562	20.8227	23.3186
12	16.1965	19.0338	20.7841	23.2583
13	16.1980	18.7334	20.6527	22.8507
14	16.3157	18.5865	20.8022	22.4769
15	17.1021	19.4312	21.4102	23.3467
16	16.0496	18.8406	20.6903	23.4441
17	16.5324	19.4555	21.0825	23.7913
18	16.5298	19.0285	20.8700	22.9671
19	16.0513	18.7433	20.6914	23.1957
20	17.3220	19.3345	21.8899	23.6295
21	15.9728	18.7868	20.6429	23.0883
22	16.0207	18.5999	20.6400	22.9376
23	16.3145	18.6423	20.7934	22.8149
24	16.1278	18.5336	20.6561	22.9110
Avg	16.2767	18.8668	20.8394	23.1159

By using the estimated color difference channel $\hat{\mathbf{u}}_c$, the primary color channels can be obtained as

$$\hat{\mathbf{c}} = \hat{\mathbf{u}}_c + \hat{\mathbf{w}}. \tag{13}$$

Experimental Result

To demonstrate the superiority of our work, we compared the result images from the proposed method with those from Bayer CFA. For a fair comparison, Kodak test images (512 × 768) shown in Fig. 4 are used for the objective evaluation of the proposed method. 15dB and 20dB noise are added to the test images to simulate the low light condition. At this time, the W channel is assumed that the sum of the R, G, and B channels. With the full-resolution noisy R, G, B, and W channels, we generated the

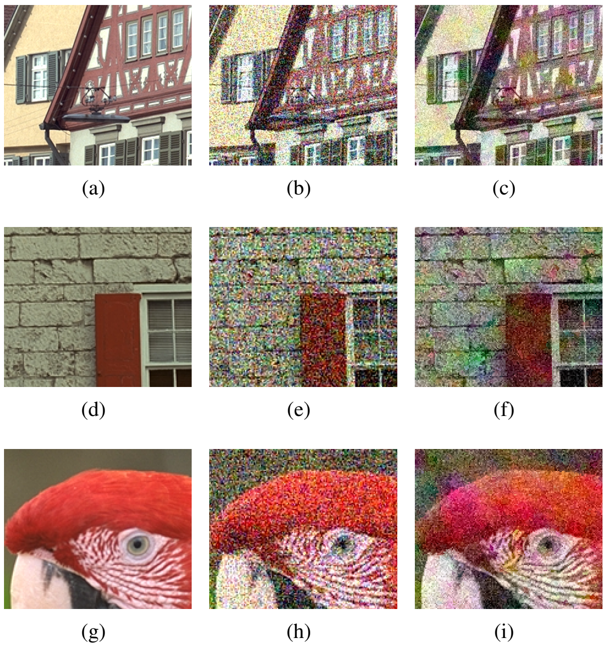


Figure 5. *Experiment results of Kodak images with 15dB noise: (a), (d), (g) original images, (b), (e), (h) Bayer results [10], and (c), (f), (i) Proposed results.*

sampled images of Bayer CFA and the proposed RGBW CFA, respectively. After that, Both sampled images are demosaicked by DLMMSE [10] and the proposed colorization based method, respectively. In the implementation of our scheme, the number of the color seeds for the R, G, and B channels is 6144, repectively, which means only 4.69% of the pixels randomly sample the primary color channels, and the rest of pixels(95.31%) sampled the W channel. We assess the quality of reconstructed images using PSNR given by

$$PSNR = 10 \times \log_{10}\{255^2/\text{MSE}\} \tag{14}$$

It can be seen from Table 1 that the estimates of the primary color channels are significantly improved by the proposed method. On average the improvement is 2.5901, and 2.2765 dB over the result of Bayer CFA in PSNR. As shown in Fig. 5, and 6, the visual quality of images from the proposed method is better than that from Bayer CFA

As a asssessment in the real low light condition, we also obtained the original R, G, B, and W full-resolution data using the four optical filters which selectively transmit light of the R, G, B, and whole visual bands respectively. After that, we sample the R, G, B, and W pixels corresponding to Bayer and the proposed RGBW CFA patterns. To make the extremely low light condition, we obtained the data in the 1lux illumination. Figure 7 shows that proposed algorithm performs better in terms of SNR and the object discrimination comparing with those from Bayer CFA. As shown in Fig. 7 (c), (f), and (i) the flat region, the variance of noise in the reconstructed image from the proposed method is quite lower than that from the Bayer result. In addition, details in the image such as the characters, lines, and small objects are discriminable in the results of the proposed method, while those are not in the Bayer results.

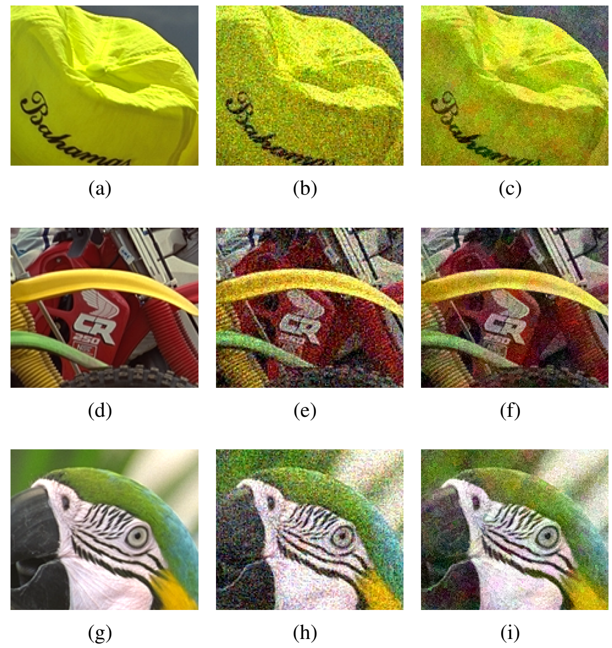


Figure 6. *Experiment results of Kodak images with 20dB noise: (a), (d), (g) original images, (b), (e), (h) Bayer results [10], and (c), (f), (i) Proposed results.*

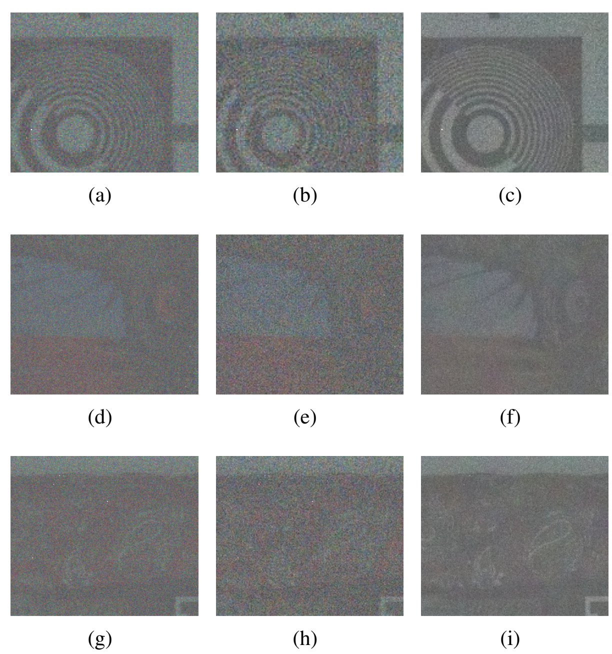


Figure 7. *Experiment results of 1 lux low light condition: (a), (d), (g) original images, (b), (e), (h) Bayer results [10], and (c), (f), (i) Proposed results.*

Conclusion

In this paper, we proposed a colorization based demosaicing algorithm which is optimized to a RGBW CFA pattern, so that it is possible to obtain high-SNR color image. Using the colorization technique, color images are able to be reconstructed by a small number of original color seeds which are randomly distributed, while the majority of the pixels sample the white channel. Comparing with the Bayer based results, image details are much more preserved with keeping the original color in the low light condition. For this reason, it is prospective to be applied in surveillance camera area.

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)

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