LETTER

An Improved White-RGB Color Filter Array Based CMOS Imaging System for Cell Phones in Low-Light Environments

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SUMMARY In this paper, a novel White-RGB (WRGB) color filter array-based imaging system for cell phone is presented to reduce noise and reproduce color in low illumination. The core process is based on adaptive diagonal color separation to recover color components from a white signal using diagonal reference blocks and location-based color ratio estimation in the luminance space. The experiments, which are compared with the RGB and state-of-the-art WRGB approaches, show that our imaging system performs well for various spatial frequency images and color restoration in low-light environments.
key words: *digital camera, CFA design, WRGB CFA, adaptive diagonal color separation*

1. Introduction

A basic trend toward large megapixel counts of cell phone within smaller CMOS Image Sensors (CISs) results in substantial degradation of sensitivity. Quality issues, such as blurring and noise, are generated due to the decrease in the photodiode area [1], especially in low luminance environments. In contrast to conventional post-processing-based image enhancement methods [2], [3], Color Filter Array (CFA)-based approaches directly address these issues using high-sensitivity sensors, and thus have become increasingly popular with consumer electronics manufacturers [4].

The most commonly-used Bayer CFA imaging system [5] (Fig. 1 (a)) provides information on the intensity of light in the red, green, and blue (RGB) wavelength regions. This reflects the fact that RGB wavelengths are close to the human luminance frequency response. However the energy of the luminance is still attenuated by as much as two-thirds when passing through the color filter.

In order to achieve a high transmission ratio in visible spectrum, White-RGB (WRGB) imaging systems [6]–[8] replace one of the green pixels of the Bayer CFA with a "white pixel" (Fig. 1 (d)). Through the use of a transparent film instead of a green color filter, a high signal-to-noise ratio (SNR) is maintained in low luminance. Compared with the 4-by-4 CFA (Fig. 1 (e) (f)), the 2-by-2 CFA is much briefer to be embedded in conventional imaging system due to its Bayer-like structure. Nevertheless, the color reproduction performance of two of these systems [6], [7], is not ideal since the average based color separation method is not robust. Another training approach has been proposed to address the color issue in the third system [8], however it is not suitable for implementation in cell phone due to its high complexity.

In this article, we proposed an improved WRGB CFA imaging system for cell phones. We focused on the resolution issue and color reproduction performance in low-light environments.

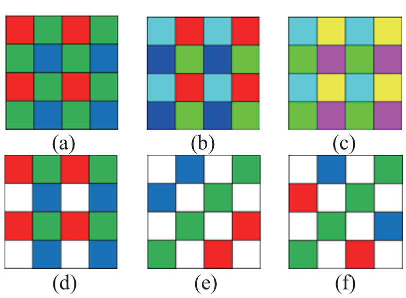

Fig. 1 Various types of CFAs. (a) Bayer CFA [5], (b) Red, Green, Blue, and Emerald (RGBE) CFA, (c) Cyan, Yellow and Magenta (CYYM) CFA, (d) the Bayer-like 2-by2 White, Red, Green, and Blue (WRGB) CFA [6]–[8] discussed in this paper, (e) Kodak 2.0 4-by-4 WRGB CFA [9], (f) Sony 4-by-4 WRGB CFA [10].

2. WRGB CFA Image System

A WRGB imaging system includes three major parts: WRGB CFA, sensor back-end processing, and remaining processing blocks (Fig. 2).

The layout of the WRGB CFA is Bayer-like, except that one of the green filters is replaced by a transparent film designed to obtain white signal. The quantum efficiency of the WRGB CFA (Fig. 3) shows that the white pixel has higher spectral sensitivity than any of the color pixels in the

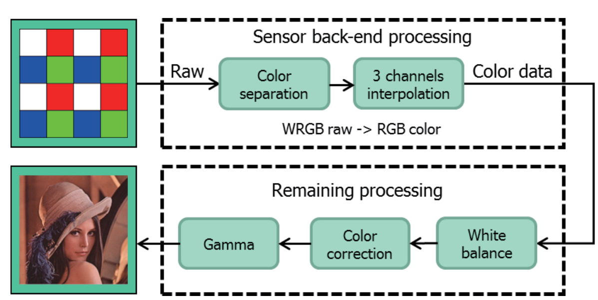

Fig. 2 Diagram of a WRGB-based imaging system.

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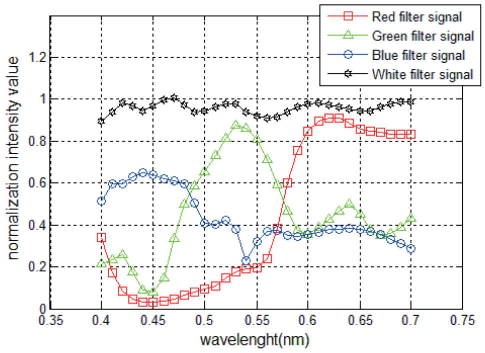


Fig. 3 Measured quantum efficiency of the White-RGB CFA.

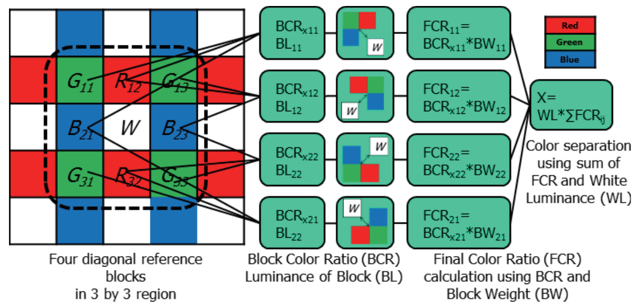


Fig. 4 Illustration of the proposed color separation scheme.

wavelength of 450~650 nm. This spectrum represents the spectral sensitivity of the photodiode itself and thus, the raw data of the white pixel includes only luminance information (no color information).

The remaining processing (including white balance, gamma correction and so on) is based on the conventional Bayer signal processing approaches. Thus sensor back-end processing is utilized to transform the white signal into three channels color data. Reproduction of the color information from the white signal is a major challenge for the WRGB CFA-based imaging system.

3. Adaptive Diagonal Color Restoration

Many previous studies have attempted to obtain this color information [6]–[8]. The first category [6] describes the relationship between the white and color components based on optical theory, as shown by Eq. (1). In Eq. (2), X (indicating red, green, or blue) color components are obtained via averaging approaches based on Eq. (2).

$$White\ signal = \sum Red + Green + Blue \tag{1}$$

$$X_w = W * \frac{X_{average}}{R_{average} + G_{average} + B_{average}} \tag{2}$$

The chrominance of the average based approach in high spatial frequency images is homogeneous, thus an averaging-based approach cannot address edge blur problems. Although another edge-based color separation [7] can attempt to avoid the influence of blur, almost two-thirds of the color information is lost because red and blue components are ignored. Furthermore, the increasing calculation of edge detection-based approach makes it difficult to implement for cell phones.

To address the issues mentioned above, a novel color restoration method was proposed for the WRGB CFA imaging system. This approach focuses on the color performance enhancement for the conventional WRGB-based imaging system utilizing an adaptive diagonal color separation method.

A recently popular edge-preserving strategy is the bilateral filter [11]. The weight-based theory can affect the edge issues of color separation mentioned above, even though it has been used for image enhancing approaches such as denoising. To modify the bilateral filter for the color separation approach, four specific issues should be considered:

1) Unlike denoising issues, not all of the pixels should be filtered, on the contrary, the white pixel should be the process target, and will be the sole center of the filter.

2) Since the input of the system is not a complete image (each pixel has the all information from three channels), only one channel data was allowed for one pixel. Thus a set of reference pixel is necessary.

3) Lab space, which is unusually utilized for the color intensity weight calculation is not appropriate for the WRGB sensor. A novel color intensity index is needed because the L cannot be calculated based on only one channel of color, especially for the white channel, which cannot be simply transformed to normal L.

4) Space weight is meaningless for the complex distribution of the raw pixels. Furthermore the same distance between the reference block and the center white pixel can simplify the calculation.

Figure 4 illustrates the proposed color separation framework. The color separation is carried out within a 3-by-3 region, the center of which is a white pixel. Considering that rectangular reference blocks in conventional methods [6]–[8] are not three channels complete, to unify the blocks, four diagonal reference blocks are used (Fig. 4). Because only one red (the same applies to green and blue) pixel was used in the reference block, not only is there no color information loss, but the averaging calculation is also unnecessary. Furthermore, the uniform calculation unit that uses the uniform reference block reduces the complexity of CIS implementation.

To describe the spatial frequency characteristics within the N-by-N reference block, a novel white luminance (L_w) space was proposed. It is not simply defined by the mathematical relationship of RGB channels, but is defined by the intensity of the white pixel and the relationship between the spectrum characteristics between the four WRGB channels. The following distance between the center white pixel and the (i, j) diagonal reference block in the (k_v, k_n) grid (T by T) is proposed:

$$D_{ij}(k_v, k_h)^2 =$$

$$\left(\begin{bmatrix} R\left(k_vT+(T-1)(i-1),\ k_hT+(T-1)(j-1)\right) \\ G\left(k_vT+1,\ k_hT+(T-1)(j-1)\right) \\ B\left(k_vT+(T-1)(i-1),\ k_hT+1\right) \end{bmatrix} L_{wt}^T - L_w\left(k_v+\frac{T}{2},\ k_h+\frac{T}{2}\right)\right)^2 \tag{3}$$

where L_{wt} is a translation matrix, which is used to obtain the luminance projection in the luminance line.

The color relationship in Eq. (1) indicates these four channels (White, Red, Green and Blue) are not independent. Therefore, four-dimensional signals in WRGB space can be transformed into one dimension in the luminance domain using the translation matrix L based on the characteristic of the sensor spectrum (Fig. 3).

As shown in Fig. 5 (b), the spatial frequency characteristics can be described by the distance as follows:

1) Homogeneous: The locations of white pixels are close to those of the reference blocks in the luminance line.

2) Morph: The distribution is uniform, with the white pixel as the center.

3) Sharp Edge: Several of the reference blocks are close to the white pixel, while others are far away.

Based on the distance method, the block weights (BWs) of the four diagonal reference blocks are given by Eq. (4).

$$BW_{ij}(k_v, k_n) = \frac{\exp(D_{ij}(k_v, k_h))^{-1}}{\sum_{m=1}^{N}\sum_{n=1}^{N}\exp\left(D_{mn}(k_v, k_h)\right)^{-1}} \tag{4}$$

A remarkable property of Eq. (4) is that the BW depends on the distance between the reference blocks and the white pixel: the smaller the distance, the larger the BW.

$$FCR_R = \sum_{i=1}^{N}\sum_{j=1}^{N}\frac{R\left(k_vT+(T-1)(i-1),\, k_hT+(T-1)(j-1)\right)}{L_w\left(k_v+\frac{T}{2},\, k_h+\frac{T}{2}\right)} * BW_{ij}(k_v, k_h)$$

$$FCR_G = \sum_{i=1}^{N}\sum_{j=1}^{N}\frac{G\left(k_vT+1,\, k_hT+(T-1)(j-1)\right)}{L_w\left(k_v+\frac{T}{2},\, k_h+\frac{T}{2}\right)} * BW_{ij}(k_v, k_h)$$

$$FCR_B = \sum_{i=1}^{N}\sum_{j=1}^{N}\frac{B\left(k_vT+(T-1)(i-1),\, k_hT+1\right)}{L_w\left(k_v+\frac{T}{2},\, k_h+\frac{T}{2}\right)} * BW_{ij}(k_v, k_h) \tag{5}$$

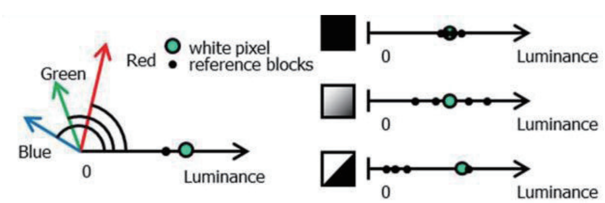


Fig. 5 Relationship between center white pixel and diagonal reference blocks in the luminance line. (a) four to one dimensional transformation of the luminance line, (b) the spatial frequency characteristics described by the luminance distance, which are, homogeneous, morph, and edge, from top to bottom.

The final color ratio (FCR) can be described by the multiplication of the color ratio and the BW via Eq. (5). Then, the X color component from the white pixel raw data is estimated by Eq. (6).

$$White_X = WhiteSignal * FCR_X \tag{6}$$

If W is saturated, the intensity of W, which is always 255, will be meaningless. Thus color information of W is calculated using the average color of the reference blocks. Considering the region of saturation is usually high bright and smooth, the blur caused by averaging is not sensitivity for human view.

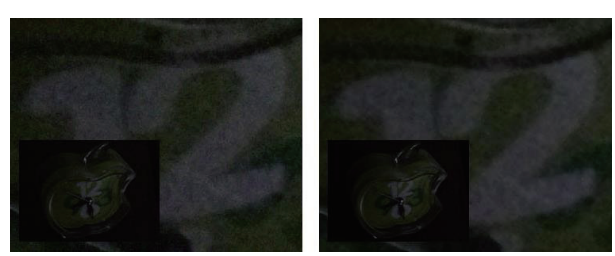
4. Experiments

The raw data taken by the imaging system described in Sect. 2 by the SK Hynix WRGB CFA sensor and Bayer RGB CFA sensor were recorded. Proposed adaptive diagonal color separation was used to recover color components and the same linear interpolation methods were utilized to obtain the final color images. Compared with Bayer CFA (Fig. 6 (a)), the result of the WRGB CFA (Fig. 6 (b)) achieved lower noise and clearer image in low-light environment.

To evaluate the color and edge performance, the color separation method of the imaging system was taken using the average-based method [6] and the proposed adaptive diagonal color separation, respectively.

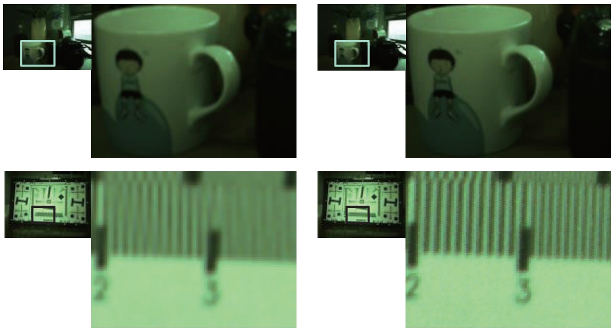
The results of subjective view (Fig. 7) and Modulation Transfer Function (MTF) of ISO chart in Table 1 indicated that the images obtained with the proposed method are sharper, especially around the high frequency regions circled by blocks.

Finally, the Peak Signal-to-Noise Ratio (PSNR) was used to evaluate the synthetic image quality of the proposed WRGB CFA-based imaging system. Raw images of the WRGB and RGB sensors in a low light environment were used to input the average [6], edge detection [7] and proposed methods. Then, a high luminance image of the RGB sensor, with less noise, was treated as a signal after being adjusted to the same luminance level as the previous images.



(a) (b)

Fig. 6 Images in low-light. (a) image of Bayer CFA sensor, (b) image of WRGB CFA sensor.



(a) Method [6]   (b) Proposed method

Fig. 7 Image results of edge region performance evaluation using (a) the average-based method and (b) the proposed method.

Table 1 Frequency evaluation of the average [6] and proposed imaging system using MTF.

Regions in ISO Chart	No.3	No.4	No.5	No.6
Average [6]	0.9167	0.9426	0.9508	0.9652
Prop.	0.6786	0.8231	0.8846	0.9244

Table 2 PSNR of the proposed imaging system compared to conventional approaches.

Test image	*Macbeth chart*			*Lenna*			*House*		
	R	G	B	R	G	B	R	G	B
Bayer CFA	24.92	30.63	26.26	25.25	30.53	25.41	25.33	31.04	25.32
Average [6]	30.83	32.41	31.95	31.01	32.84	31.83	31.25	32.53	30.89
Edge Det.[7]	31.75	32.80	33.01	32.12	33.01	33.20	32.04	33.22	31.94
Prop.	31.89	33.43	33.24	32.14	33.55	33.21	32.85	34.01	32.20

Three images were selected as examples in Table 2.

The PSNRs of R, G, and B increased by 6db, 2db, and 6db respectively, compared with those of the Bayer-CFA because the white filter of the proposed method had higher sensitivity. Furthermore, a higher PSNR was obtained for R and B, since more color information was reserved compared with method [7] due to the better performance around the edge of the proposed adaptive color separation method.

5. Conclusions

In this paper, an improved WRGB CFA-based imaging system is proposed for cell phones. The goal was to address the low-light issues using a white conventional approaches. Due to the high sensitivity of the white filter, a high intensity is achieved in low-light environments. Furthermore, an adaptive diagonal color separation method was designed to solve the blurring and color loss issues of the conventional WRGB imaging methods [6]–[8]. Finally, the PSNR showed good synthetic imaging performance. Thus, the proposed imaging system is feasible for integration into a cell phone to improve the imaging quality in low-light environments.

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