An Efficient Combined Demosaicing and Zooming Algorithm for Digital Camera

King-Hong Chung, Yuk-Hee Chan, Chang-Hong Fu and Yui-Lam Chan

Department of Electronic and Information Engineering
The Hong Kong Polytechnic University, Hong Kong

***Abstract*—Color demosaicing and digital zooming are common processes in digital cameras and they often employ similar interpolation concepts based on the information extracted from the raw sensor data. Realizing them independently is not efficient as separate extraction processes are required. It may also cause inconsistent utilization of the raw sensor data in different stages. This paper presents a low-complexity combined algorithm which directly extracts edge information from raw sensor data and exploits it consistently and efficiently in both demosaicing and zooming. The proposed algorithm can produce zoomed full-color images and zoomed CFA images with outstanding performance as compared with conventional approaches.**

Index Terms—*Interpolation, Color Filter Array, Cameras*

I. INTRODUCTION

Image sensors covered with Bayer color filter array (CFA) [1] are widely used nowadays in many portable electronic devices like digital cameras and mobile phones to acquire scene. Their output images (CFA images) contain only one color component at each pixel location as shown in Fig. 1. To convert them to full-color images, the two missing color components of each pixel have to be estimated by color demosaicing [2-7].

Traditionally, to produce a zoomed full-color image, digital zooming is performed after demosaicing as shown in Fig. 2a. The zooming can be achieved by applying either plane-wise interpolation [8] or vector color interpolation [9] on the demosaiced image. However, demosaicing always introduces visual artifacts such as blurred edges and false colors [10]. These artifacts may be amplified during the zooming process and the quality of the resultant zoomed image can be very poor in regions of complicated details.

Recently, an alternative approach [11,12] to produce a zoomed full-color image has been proposed as shown in Fig. 2b to improve the zoom performance and to reduce the realization complexity. It zooms the CFA image first so that conventional demosaicing technique can be applied to the enlarged CFA image to produce a zoomed full-color image.

Both approaches carry out demosaicing and zooming individually. As demosaicing and zooming often employs similar interpolation concepts, performing these two processes independently may cause inconsistent and inefficient utilization of the raw sensor data.

In this paper, a simple combined demosaicing and zooming method is proposed as shown in Fig. 2c to solve this problem. By sharing the edge information extracted directly form the raw sensor data, the green plane in the CFA image is first enlarged effectively and efficiently. The red and the blue missing samples in the enlarged image are then estimated with the interpolated green plane and the color difference model [6]. Simulation results show that the proposed algorithm is superior to conventional approaches, which are generally combinations of different demosaicing and zooming algorithms, in producing zoomed full-color images in terms of output image quality and complexity.

This paper is organized as follows. In Section II, a green plane demosaicing scheme, which is used in the proposed combined demosaicing and zooming algorithm, is presented. The details of our combined demosaicing and zooming algorithm is then described in Section III. Experimental results and a complexity analysis are respectively provided in Section IV and V.

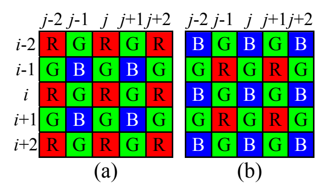

Fig. 1 – Two 5×5 regions of Bayer pattern having centers at (a) red and (b) blue samples

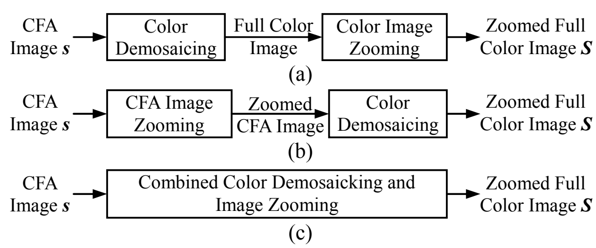

Fig. 2 – Image zooming methods: (a) zooming after demosaicing, (b) demosaicing after zooming, and (c) the proposed combined demosaicing and zooming

II. GREEN PLANE DEMOSAICING SCHEME

The proposed scheme is designed based on the demosaicing method proposed in [7]. It interpolates the missing green samples in a CFA image by selecting one of the three directional second-order Laplacian interpolators [2]. As an example, the missing green sample of the center pixel (i,j) in Fig.1a is estimated with one of the following directional interpolators.

$$\text{Horizontal}\,(H): g^H_{i,j} = \frac{G_{i,j-1}+G_{i,j+1}}{2} + \frac{2R_{i,j}-R_{i,j-2}-R_{i,j+2}}{4} \quad (1)$$

$$\text{Vertical}\,(V): \quad g^V_{i,j} = \frac{G_{i-1,j}+G_{i+1,j}}{2} + \frac{2R_{i,j}-R_{i-2,j}-R_{i+2,j}}{4} \quad (2)$$

$$\text{Diagonal}\,(D): \quad g^D_{i,j} = \frac{g^H_{i,j}+g^V_{i,j}}{2} \quad (3)$$

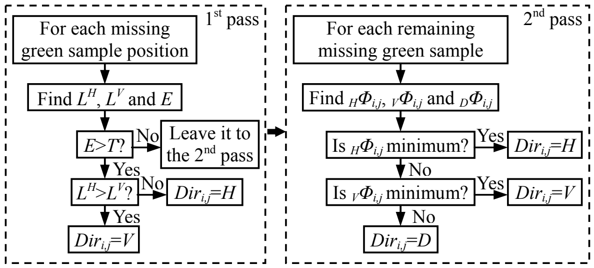

Fig. 3 – Procedures for determining the direction to interpolate a missing green component in the proposed green plane demosaicing scheme

The selection of the interpolator is critical to the demosaicing performance [7]. The proposed scheme exploits a two-pass decision scheme. Fig. 3 summarizes the workflow of selecting an interpolator for a particular pixel in different passes of the proposed scheme. The details are as follows.

Pass 1

In this pass, all the pixels in sharp edge regions are processed. Similar to the algorithm proposed in [7], the scheme starts with determining the horizontal and vertical edge levels, L^H and L^V, of a pixel by using the local intensity gradient and the color difference information in the pixel's 5×5 local region. As an example, for pixel (i,j) in Fig. 1a, we have

$$L^H = \sum_{k=\pm1,\pm2}\sum_{m=-2}^{2}\left|X_{i+m,j+k}-X_{i+m,j}\right| \quad \text{and} \quad L^V = \sum_{k=\pm1,\pm2}\sum_{m=-2}^{2}\left|X_{i+k,j+m}-X_{i,j+m}\right| \tag{4}$$

where $X_{p,q}$ denotes the known sample at pixel position (p,q).

The edge level ratio $E=\max(L^H/L^V, L^V/L^H)$ is then computed and compared with a predefined threshold T. If it is larger than T, the pixel is said to be in a sharp edge region. Its interpolation direction $Dir_{i,j}\in\{H,V,D\}$ and the missing green component $g_{i,j}$ are then determined as

$$\begin{cases} Dir_{i,j}=H & \text{and} \quad g_{i,j}=g^H_{i,j} \quad \text{if } L^V/L^H>T \\ Dir_{i,j}=V & \text{and} \quad g_{i,j}=g^V_{i,j} \quad \text{if } L^H/L^V>T \end{cases}. \tag{5}$$

Otherwise, it is said to be in a flat or texture region and left behind for being processed in Pass 2. For the threshold, experimental results show that T=2 can provide a good result.

Pass 2

In the 2nd pass, all the pixels whose green components are still missing in the CFA image are processed in a raster scan manner. For each of them, 1st absolute moments of the color difference values of the pixels along the axes of a 9×9 local region are determined for its interpolator selection. Particularly, for the case shown in Fig.1a, the horizontal and vertical absolute moments for pixel (i,j), say ${}_H\Phi_{i,j}$ and ${}_V\Phi_{i,j}$, are defined as follows.

$${}_H\Phi_{i,j} = \sum_{k=-2}^{2}\left|d_{i,j+2k}-\frac{1}{5}\sum_{n=-2}^{2}d_{i,j+2n}\right| \quad \text{and} \quad {}_V\Phi_{i,j} = \sum_{k=-2}^{2}\left|d_{i+2k,j}-\frac{1}{5}\sum_{n=-2}^{2}d_{i+2n,j}\right| \tag{6}$$

where $d_{p,q}$ is a color difference value of pixel (p,q). The values of $d_{i,j+2k}$ and $d_{i+2k,j}$ for k∈{±2,±1,0} are computed as

$$d_{i,j+2k} = \begin{cases} R_{i,j+2k}-g_{i,j+2k} & \text{if } g_{i,j+2k} \text{ was estimated} \\ R_{i,j+2k}-g^H_{i,j+2k} & \text{otherwise} \end{cases}$$

and

$$d_{i+2k,j} = \begin{cases} R_{i+2k,j}-g_{i+2k,j} & \text{if } g_{i+2k,j} \text{ was estimated} \\ R_{i+2k,j}-g^V_{i+2k,j} & \text{otherwise} \end{cases} \tag{7}$$

As for the diagonal absolute moment ${}_D\Phi_{i,j}$, since there is no green sample available along the diagonal axes of the window, it is evaluated as

$${}_D\Phi_{i,j} = \frac{1}{2}\sum_{k=-2}^{2}\left|d_{i,j+2k}-\frac{1}{5}\sum_{n=-2}^{2}d_{i,j+2n}\right| + \frac{1}{2}\sum_{k=-2}^{2}\left|d_{i+2k,j}-\frac{1}{5}\sum_{n=-2}^{2}d_{i+2n,j}\right|. \tag{8}$$

where the color difference $d_{p,q}$ is found in a way similar to that in eqn.(7) but the preliminary green estimates $g^D_{i,j+2k}$ and $g^D_{i+2k,j}$ are utilized instead of $g^H_{i,j+2k}$ and $g^V_{i+2k,j}$ respectively.

As color differences are more or less the same within a small region [6], the interpolation direction for pixel (i,j) should be the one which provides the minimum absolute moment of color differences. Hence, the missing green component of pixel, $g_{i,j}$, is determined as follows.

$$\begin{cases} Dir_{i,j}=H \text{ and } g_{i,j}=g^H_{i,j} & \text{if } {}_H\Phi_{i,j}=\min({}_H\Phi_{i,j},{}_V\Phi_{i,j},{}_D\Phi_{i,j}) \\ Dir_{i,j}=V \text{ and } g_{i,j}=g^V_{i,j} & \text{if } {}_V\Phi_{i,j}=\min({}_H\Phi_{i,j},{}_V\Phi_{i,j},{}_D\Phi_{i,j}) \\ Dir_{i,j}=D \text{ and } g_{i,j}=g^D_{i,j} & \text{if } {}_D\Phi_{i,j}=\min({}_H\Phi_{i,j},{}_V\Phi_{i,j},{}_D\Phi_{i,j}) \end{cases} \tag{9}$$

For the case in which the concerned pixel is the center pixel of a region shown in Fig. 1b, one can treat blue samples as red samples and follow the above procedures to estimate the missing green component. A complete demosaiced green plane is obtained after Pass 2.

III. Combined Demosaicing and Zooming Algorithm

As the green channel provides double samples than the others in a CFA image, the proposed combined algorithm starts with green-plane interpolation. The interpolation of the red plane and the blue plane then follows. Assume that a CFA image $\boldsymbol{s}$ of size $M\times N$ has to be enlarged to a zoomed full-color image $\boldsymbol{S}$ of size $\lambda M\times\lambda N$, where $\lambda=2^z$ is a zooming factor and z is a positive integer. In this paper, λ=2 is selected for simplicity to facilitate the following discussion.

For the sake of reference, hereafter, pixels at location (p,q) in image $\boldsymbol{s}$ and image $\boldsymbol{S}$ are respectively represented by $s_{p,q}=\{s_{r(p,q)},s_{g(p,q)},s_{b(p,q)}\}$ and $S_{p,q}=\{S_{r(p,q)},S_{g(p,q)},S_{b(p,q)}\}$, where $s_{k(p,q)}$ and $S_{k(p,q)}$ for $k=r$ (red), g (green) and b (blue) donate corresponding color components.

Fig. 4 shows how image $\boldsymbol{S}$ is obtained from CFA image $\boldsymbol{s}$ step by step in different stages for reference, where the circles with segmented edges denote the pixels to be processed in the following processing stage.

A. Green (G) Plane Interpolation

In the proposed algorithm, the green plane demosaicing scheme described in Section II is carried out first. It results in a direction map indicating the interpolation directions for the missing green components and a complete demosaiced green plane of image $\boldsymbol{s}$ as shown in Fig. 4b. Median filtering is then applied to the color difference planes of image $\boldsymbol{s}$ to refine the demosaiced green plane. For a pixel which is in the middle of the pattern shown in Fig. 1a, its demosaiced green component $s_{g(i,j)}$ is refined by

$$s_{g(i,j)} = \text{median}(d_{i,j},d_{i-2,j},d_{i+2,j},d_{i,j-2},d_{i,j+2})+s_{r(i,j)} \tag{10}$$

where $d_{m,n} = s_{g(m,n)} - s_{r(m,n)}$ represents the color difference of pixel (m,n). Note that $s_{r(m,n)}$ in eqn.(10) is actually a raw sensor component in image $\boldsymbol{s}$. To refine a pixel which is in the middle of the pattern shown in Fig. 1b, the same refinement step can be used after replacing red samples with corresponding blue samples. We have $d_{m,n} = s_{g(m,n)} - s_{b(m,n)}$ in this case.

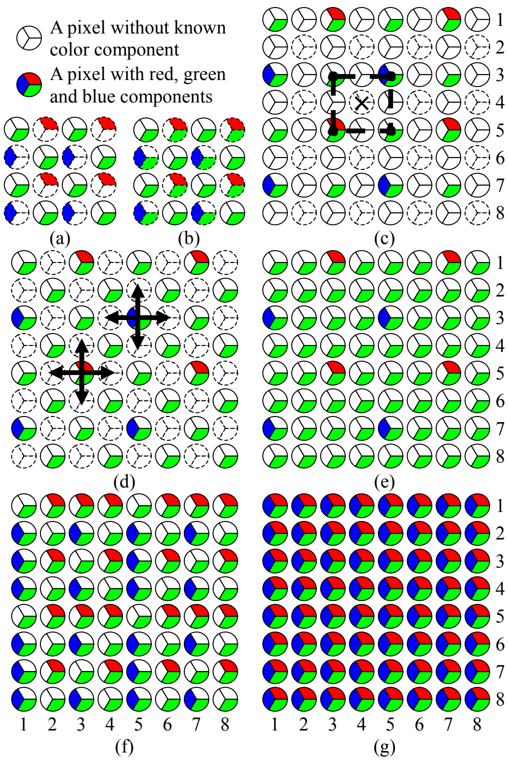

Fig. 4 – Spatial arrangement of the intermediate results: (a) raw sensor output CFA image, (b) after demosaicing green-plane, (c) after spatial expansion, (d) after estimating diagonal green components, (e) after estimating all green components, (f) intermediate result containing the enlarged CFA image and (g) final enlarged full-color image

The enhanced partially-demosaiced image $\boldsymbol{s}$ is then expanded to form an image of the same size as the zoomed image $\boldsymbol{S}$. In particular, we have $S_{2i-1,2j-1}=s_{i,j}$ for all (i,j) in image $\boldsymbol{s}$. Fig. 4c shows the spatial arrangement of the output of this stage.

Up to this moment, three-fourth of the green components are still missing. The pixels which marked with segmented edges are interpolated first as they are surrounded by four known green values which form a square support as shown in Fig. 4c. Let $S_{g(p,q)}$ be one of them and $\zeta=\{(p\pm1,q\pm1)\}$ be its support. Its value is then determined by

$$S_{g(p,q)} = \sum_{(a,b)\in\zeta} w_{a,b} S_{g(a,b)} \Big/ \sum_{(a,b)\in\zeta} w_{a,b} \tag{11}$$

where $w_{a,b}$ is a weighting factor defined as

$$w_{a,b} = \sum_{\substack{(m,n)\in\zeta \\ (m,n)\neq(a,b)}} \left(D_{\max} - \delta_{a,b}^{m,n}\right) + 1 \tag{12}$$

In eqn.(12), $\delta_{a,b}^{m,n} = \left|g_{m,n} - g_{a,b}\right|$ is actually the absolute difference between any two known green components in ζ and D_{max} is the maximum value in $\{\delta_{a,b}^{m,n} \mid (m,n)\neq(a,b)$ and $(m,n),(a,b)\in\zeta\}$. Note that the weights are determined in a way that a known green component $S_{g(a,b)}$ will contribute less to the estimate of $S_{g(p,q)}$ if it is dissimilar to the other known green components in ζ. This idea is similar to that of the edge-sensing weighting scheme used in [11,12] where the weights are computed as the reciprocal values of gradients. However, the complexity of the proposed scheme is lower as division is not required to determine the weights. Fig. 4d shows the spatial arrangement of the output of this stage.

The remaining missing green components are then interpolated by simple directional bilinear interpolation. Let (p,q) be one of their locations. As shown in Fig. 4d, for each of them, there is a neighboring pixel whose green component was determined when demosaicing the green plane of CFA images. Let the location of this neighboring pixel of $S_{p,q}$ be (i,j). $S_{g(p,q)}$ is then estimated as follows.

$$S_{g(p,q)} = \begin{cases} \left(S_{g(p,q-1)} + S_{g(p,q+1)}\right)/2 & \text{if } \Gamma(S_{g(i,j)}) = H \\ \left(S_{g(p-1,q)} + S_{g(p+1,q)}\right)/2 & \text{if } \Gamma(S_{g(i,j)}) = V \\ \frac{1}{4}\sum_{k=\pm1}(S_{g(p,q+k)} + S_{g(p+k,q)}) & \text{if } \Gamma(S_{g(i,j)}) = D \end{cases} \tag{13}$$

where $\Gamma(S_{g(i,j)})$ denotes the interpolation direction for estimating $S_{g(i,j)}$ when demosaicing the green plane of $\boldsymbol{s}$.

In eqn.(13), by taking the advantage of the edge consistency in a small region, missing green components in a local region are interpolated with the same direction. This process provides a simple but effective means to preserve edge feature in the zooming result. Fig. 4e shows the spatial arrangement of the output of this stage where all the missing green components of image $\boldsymbol{S}$ are determined.

B. Red (R) and Blue (B) Plane Interpolation

To constitute the missing red and blue components in Fig. 4e, the color difference model used in [6] is employed. For each pixel whose red (blue) component is missing, its green-to-red (green-to-blue) color difference value is bilinearly interpolated from the neighboring pixels having known red (blue) CFA components and its intensity value can then be determined. Fig. 4f shows the intermediate result where some missing red and blue components are estimated first to allow image $\boldsymbol{S}$ to be stored in CFA format well before its full-color image is finally determined as shown in Fig. 4g.

IV. Simulation Results

Simulation was carried out to evaluate the performance of the proposed algorithm. Fig. 5 shows twenty-four 24-bit digital color images of size 512×768 each. They were first down-sampled to half the original sample-rate and then sub-sampled according to the Bayer CFA pattern to form a set of CFA testing images of size 256×384. The small CFA images were then processed with different approaches to produce zoomed full-color images of size 512×768.

In our simulation, the bilinear zooming method (BI) [8] were combined with some state-of-the-art demosaicing methods such as [5] (BICD), [2] (ACPI), [3] (AP) and [4] (AHDDA) to produce zoomed full-color images for comparison. Besides, the algorithm proposed in [12] (DCZPS) was also realized. The color peak signal-to-noise ratio

(CPSNR) [7] and the CIELab color difference (ΔE) [13] were utilized to measure the performance of various approaches.

Table 1 tabulates the averaged ΔE and CPSNR performance of various algorithms. It shows that the proposed algorithm produces the best average performance among the testing algorithms. Fig. 6 shows the zooming results of image 19 for visual comparison. It shows that the proposed algorithm outstandingly preserves the image features with less color artifacts. For example, the texture features in the fence region can be completely reproduced by the proposed algorithm.

Fig. 5 – Twenty-four digital color images (Refers as image 1 to image 24, from top-to-bottom and left-to-right)

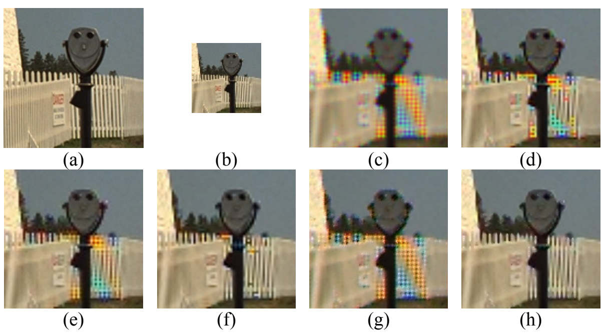

Fig. 6 – Part of the processing results of Image 19: (a) the original, (b) the input CFA image, (c) BICD+BI, (d) ACPI+BI, (e) AP+BI, (f) AHDDA+BI, (g) DCZPS and (h) the proposed algorithm.

	BICD [5]+BI	ACPI [2]+BI	AP [3]+BI	AHDDA [4]+BI	DCZPS [12]	Ours
CPSNR	25.29	27.20	27.87	27.77	25.98	28.05
ΔE	6.737	5.093	4.411	4.095	5.535	4.082

Table 1 – Average CPSNR (in dB) and ΔE performance of various algorithms

V. Computational Complexity

Table 2 lists the average number of operations per pixel required by different methods in processing the 24 testing images in our simulations. The complexity of BICD+BI and ACPI+BI is lower than that of the proposed algorithm but their output quality is poor as shown in Fig.6. The complexity of the proposed algorithm is around 25% of that of DCZPS [12]. When zooming a CFA image, the complexity of the proposed algorithm is around 67% of that of CIZBP [11]. The computation effort for the proposed algorithm to produce a zoomed full-color image is less than that required for CIZBP [11] to produce a zoomed CFA image.

The average execution time for the proposed algorithm to produce a zoomed full-color image from a 256×384 CFA image with a zooming factor of 2 on a 2.8GHz Pentium 4 PC with 512MB RAM is about 0.0733s.

Methods	**ADD**	**MUL**	**CMP**	**SHT**	**ABS**	**Total**
Producing a zoomed full-color image						
BICD+BI	5.25	0.00	0.00	4.25	0.00	**9.50**
ACPI+BI	5.87	0.00	0.38	3.49	0.99	**10.73**
AHDA+BI	16.25	2.00	9.75	8.25	1.00	**37.25**
AP+BI	64.77	7.88	0.13	32.25	0.50	**105.53**
DCZPS	67.50	43.44	0.00	0.00	16.88	**127.81**
Ours	21.53	2.04	2.75	2.91	4.58	**33.82**
Producing a zoomed CFA image						
CIZBP	25.88	14.25	0.00	0.00	4.50	**44.63**
Ours	18.78	2.04	2.75	1.54	4.58	**29.69**

Table 2 – Averaged number of operations per pixel required by various algorithms

VI. Conclusion

In this paper, a low complexity combined demosaicing and zooming algorithm is proposed. By sharing the edge information extracted directly form the raw sensor data, the green plane in the CFA image is first enlarged. The red and the blue missing samples in the enlarged image are then estimated with the interpolated green plane and the color difference model. The proposed algorithm can produce a superior result at a low complexity as compared with conventional approaches which generally perform demosaicing after zooming or zooming after demosaicing.

VII. Acknowledgement

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