A Novel Cost Effective Demosaicing Approach

R. Lukac, K.N. Plataniotis, D. Hatzinakos, and M. Aleksic

Abstract — *A unique color interpolation approach for digital still cameras is introduced and described in terms of color vectors. A new difference plane model is introduced and used in conjunction with the proposed here correction process. This avoids edge blurring while improving on the color appearance of previous methods. Experimental results indicate that the proposed method exhibits superior performance over state of-the-art color interpolation methods[1].*

Index Terms — Camera image processing, Bayer pattern, color filter array interpolation, color image restoration.

I. INTRODUCTION

COLOR image processing has aroused much interest and acclaim over the past few years. The advances in hardware and software platforms have allowed capturing and reproducing of real scenes in color as never before. Digital cameras for still images are among the most popular acquisition devices, whose commercial proliferation has a significant impact on the research in this area.

Digital color cameras acquire color information by transmitting the image through Red (R), Green (G) and Blue (B) color filters having different spectral transmittances and then sampling the resulted images using three electronic sensors, usually charge coupled devices (CCD) and complementary metal oxide semiconductor (CMOS) sensors (Fig. 1a). To reduce cost and complexity, digital camera manufacturers use a single CCD/CMOS sensor with a color filter array (CFA) to capture all the three primary colors (R,G,B) at the same time (Fig. 1b). The Bayer pattern (Fig. 2) [1], a widely used CFA, provides the array or mosaic of the RGB colors so that only one color element is available in each pixel, whereas two missing colors must be estimated from the adjacent pixels. This process is called CFA interpolation, or demosaicing [2].

In this paper, we introduce a new CFA interpolation method along with a novel vector notation of interpolation steps. The proposed edge-sensing method employs a new correlation-correction process based on a simple difference plane model. The introduced vector notation finds a support in fundamentals of color image filtering [3], and allows to describe the CFA interpolation as a compact framework.
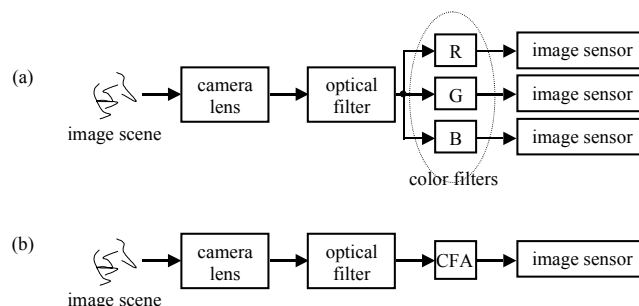
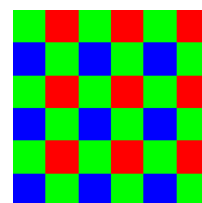Fig. 1. Digital camera systems: (a) a three-sensor device, (b) a single-sensor device.

Fig. 2. Bayer CFA pattern.

II. PROBLEM FORMULATION

Let us consider, a $K_1 \times K_2$ gray-scale image $z(i): Z^2 \to Z$ representing a two-dimensional matrix of integer samples. In the Bayer CFA pattern, half of the pixels z_i, for $i = 1, 2, ..., K_1 K_2$, correspond to the G channel, whereas the R,B channels are assigned the other half of the pixels. Assuming that $p = 1, 2, ..., K_1$ and $p = 1, 2, ..., K_2$ denote the spatial position of the pixels in vertical (image rows) and horizontal (image columns) directions, gray-scale pixels z_i can be transformed into the RGB vectors $\mathbf{x}_i = (x_{i1}, x_{i2}, x_{i3})$, for $i = (p-1)K_2 + q$, as follows:

$$\mathbf{x}_i = \begin{cases} (z_i, 0, 0) & \text{for } p \text{ odd and } q \text{ even,} \\ (0, 0, z_i) & \text{for } p \text{ even and } q \text{ odd,} \\ (0, z_i, 0) & \text{otherwise.} \end{cases} \quad (1)$$

This transformation forms a $K_1 \times K_2$ RGB image $\mathbf{x}(i): Z^2 \to Z^3$ representing a two-dimensional matrix of three-component samples. Note that the color vectors $\mathbf{x}_i$ relate to one true component varying in k from position to position, whereas other two components of $\mathbf{x}_i$ are set to zero.

To estimate the missing color components of $\mathbf{x}(i)$, a sliding supporting window $W = \{\mathbf{x}_i; i = 0, 1, ..., N-1\}$ of finite size N is considered with the sample under consideration, sample $\mathbf{x}_0$, placed in the center of the window (Fig. 3). The procedure replaces $\mathbf{x}_0$ by some function of the local neighborhood are
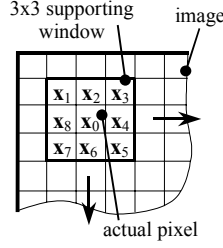
Fig. 3. Sliding supporting window.

Fig. 4. Edge-sensing scheme used in the proposed design.

$\mathbf{x}_1, \mathbf{x}_2, ..., \mathbf{x}_{N-1}$ at a time. The rationale of this approach is to minimize the local distortion and ensure the stationarity of the processes generating the image [3].

Interpolating the missing color components of the image $\mathbf{x}(i)$ constitutes the interpolated RGB image $\mathbf{y}(i) : Z^2 \rightarrow Z^3$. The objective of the interpolation process is to estimate the missing color components of $\mathbf{x}(i)$ and reconstitute the interpolated RGB image $\mathbf{y}(i)$ to be as close as possible to the desired RGB $\mathbf{o}(i) : Z^2 \rightarrow Z^3$. As in most image processing problems, a "loss function," which depends on the unavailable full RGB sample and the interpolation vector, is use to penalize errors during the procedure. It is natural to assume that if one penalizes interpolation errors through loss function, then the optimal solution is the function of the inputs that minimizes the expected average loss:

$$\text{minimize } E\left\{ \|\mathbf{o} - \mathbf{y}\|^2 \right\} \tag{2}$$

where $E\{\cdot\}$ indicates statistical expectation guaranteeing the minimum average loss or risk [2].

III. PROPOSED METHOD

It is known that the human visual system is sensitive to changes in color and edge information, which provides indication of the shape of objects in the image [3]. False colored and blurred edges introduced as result of inaccurate interpolation significantly degrade the quality of the perceived image. Therefore, efficient interpolation algorithms incorporate edge information into the interpolation process.

A number of edge-detection mechanisms, which differentiate in preferred edge directions, have been introduced in the past years. The proposed method takes advantage of an 8-direction system of [4], which determines edge-sensing weight coefficients as follows:

$$w_1 = \frac{1}{1 + \left(|z_0 - z_9| + |z_1 - z_5| \right)/(2\sqrt{2})} \tag{3}$$

$$w_2 = \frac{1}{1 + \left(|z_0 - z_{11}| + |z_2 - z_6| \right)/2} \tag{4}$$

where w_1 and w_2 denote weights in north-west and north directions (Fig 4) and $z_0, z_1, ..., z_{24}$ are original gray-scale values of $z(i)$. Weights $w_2, w_3, ..., w_8$ are calculated analogously to (3) and (4). Note that $N = 9$ relates to a 3×3 sliding window, z_0 is the acquired pixel before the
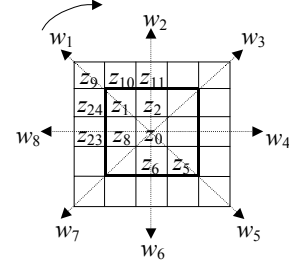
transformation (1) in the same spatial position as the RGB vector $\mathbf{x}_i$ and operator $\cong$ denotes a one to one relationship.

Using the edge-sensing scheme shown in Fig. 4, the G channel is adaptively interpolated as follows:

$$\overline{y}_{02} = \begin{cases} x_{02} & \text{if } z_0 \cong x_{0k}, \\ \sum\limits_{i=1}^{N-1} w_i' x_{i2}' & \text{otherwise} \end{cases} \tag{5}$$

where w_i', for $i = 1, 2, ..., 8$, are the normalized weighting coefficients, given by

$$w_i' = w_i / \sum_{j=1}^{N-1} w_j \tag{6}$$

Each w_i' corresponds to the pre-determined G component x_{i2}' of [4]. For illustration purposes, $x_{(1)2}'$ and $x_{(2)2}'$ corresponding to the weighting coefficients of (3) and (4) are given by

$$x_{(1)2}' = \frac{x_{(2)2} + x_{(8)2} + (z_1 - z_5)/(2\sqrt{2}) + (z_{11} - z_0 + z_{23} - z_0)/4}{2} \tag{7}$$

$$x_{(2)2}' = x_{(2)2} + (z_{11} - z_0 + z_2 - z_6)/4 \tag{8}$$

The edge sensitivity is controlled by the weighting coefficients w_i, for $i = 1, 2, ..., 8$. When no edge is positioned across the directions considered by x_{i2}', the absolute difference used in the corresponding weight w_i is small and thus x_{i2}' contributes significantly to the estimated output of (5). If x_{i2}' is defined across an edge, the corresponding w_i increases and penalizes x_{i2}' appropriately. Since the solution is unbiased [3] i) each weight is a positive number, $w_i' \geq 0$, and ii) the summation of all the weights is equal to unity:

$$\sum_{i=1}^{N-1} w_i = 1 \tag{9}$$

Interpolating the G components, we can operate on more information compared to whose of the original Bayer pattern. Since the G components determine for the most part the perceived sharpness of the digital image, adopting the color-difference model of [5], and assuming the stationarity of the processes inside the local image area of W, the missing R (or B) components of $\mathbf{x}(i)$ are given by

$$
\overline{y}_{0k} = \begin{cases} x_{0k} & \text{if } z_0 \cong x_{0k}, \\ \overline{y}_{02} + \sum_{i=1}^{(N-1)/2} w_i''\left(x_{(2i)k} - \overline{y}_{(2i)2}\right) & \text{if } z_0 \cong x_{02}, \\ \overline{y}_{02} + \sum_{i=1}^{(N-1)/2} w_i'''\left(x_{(2i-1)k} - \overline{y}_{(2i-1)2}\right) & \text{if } z_0 \cong x_{0(k\pm2)}, \end{cases} \quad (10)
$$

where $k=1$ and $k=3$ characterize the R and B channels, respectively and $w_1'', w_2'', ..., w_4''$ are the normalized weights corresponding to edges in north, east, south and west directions, whereas $w_1''', w_2''', ..., w_4'''$ are the weights corresponding to the diagonally positioned edges:

$$
w_i'' = w_{(2i)} / \sum_{j=1}^{(N-1)/2} w_{(2j)} \quad (11)
$$

$$
w_i''' = w_{(2i-1)} / \sum_{j=1}^{(N-1)/2} w_{(2j-1)} \quad (12)
$$

Since (10) produces all color components and results in the restored color image, the basic idea of (10) can be used as a correction step. Introducing a correction mechanism into the interpolation process improves contrast and accuracy of the initially interpolated G channel. Since the difference plane model of (6) is simple to implement, it is also perfectly suited to a correction stage. Thus, the correction process related to the G channel is given by

$$
y_{02} = \begin{cases} \overline{y}_{0k} + \sum_{i=1}^{(N-1)/2} w_i''\left(\overline{y}_{(2i)2} - \overline{y}_{(2i)k}\right) & \text{if } z_0 \cong x_{0k}, \\ \overline{y}_{02} & \text{otherwise} \end{cases} \quad (13)
$$

where $w_1'', w_2'', ..., w_4''$ are the same coefficients used in (6).

Considering the corrected G values of (13) the R,B update is completed using the following step:

$$
y_{0k} = \begin{cases} y_{0k} & \text{if } z_0 \cong x_{0k}, \\ y_{02} + \sum_{i=1}^{(N-1)/2} w_i''\left(\overline{y}_{(2i)k} - y_{(2i)2}\right) & \text{if } z_0 \cong x_{02}, \\ y_{02} + \sum_{i=1}^{(N-1)/2} w_i'''\left(\overline{y}_{(2i-1)k} - y_{(2i-1)2}\right) & \text{if } z_0 \cong x_{0(k\pm2)}, \end{cases} \quad (14)
$$

Since x_{0k} of (1), $\overline{y}_{0k}$ of (5) and (10); and y_{0k} of (13) and (14), for $z_0 \cong x_{0k}$ and $k=1,2,3$, are equivalent, the proposed edge-sensing correlation-correction (ESCC) method preserves all acquired (correct) values of (1) unchanged:

$$
y_{ik} = x_{ik}, \text{ if } z_i \cong x_{ik} \quad (15)
$$

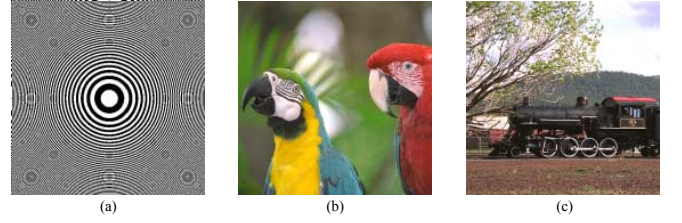leading to an efficient and attractive method.

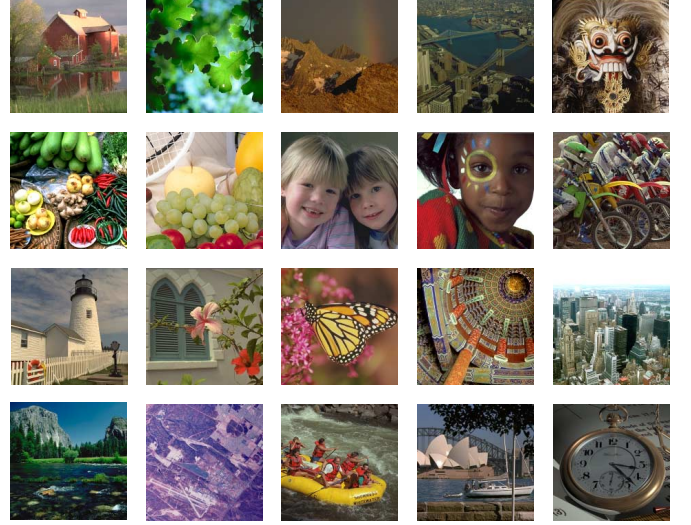**Fig. 5. Test images: (a) circular zone plate (CZP) image, (b) color image Parrots, (c) color image Train**

Fig. 6. Color image database.

IV. EXPERIMENTAL RESULTS

The proposed method is tested using the color test images shown in Fig. 5 and Fig. 6. Note that circular zone plate (CZP) image shown in Fig. 5a is a synthetic black and white image. Using this image researchers examine the performance of the interpolation methods for various edge frequency. Fig. 5b,c and Fig. 6 show the color images that have been captured using highly professional three-sensor cameras or color scanners and they have been extensively used by practitioners and researchers working in camera image processing, especially in demosaicing. This mainly due to the fact that the database: i) contains natural, real life images, ii) represents real-life scenarios and, iii) its images vary in complexity and color appearance. Note that in order to facilitate comparisons, all images have been normalized to the standard 512×512, 8-bit per channel RGB representation.

To measure the efficiency of the CFA interpolation methods objectively, a $K_1 \times K_2$ original color image $\mathbf{o}(i)$ is transformed into a $K_1 \times K_2$ Bayer image $z(i)$ as follows:

$$
z_i = \begin{cases} o_{i1} & \text{for } p \text{ odd and } q \text{ even} \\ o_{i3} & \text{for } p \text{ even and } q \text{ odd} \\ o_{i2} & \text{otherwise} \end{cases} \quad (16)
$$

where $\mathbf{o}_i = (o_{i1}, o_{i2}, o_{i3})$ denotes the color vector in the original color image $\mathbf{o}(i)$ with spatial coordinates

TABLE I
COMPARISON OF THE METHODS USING THE CZP IMAGE

Method	MSE_R	MSE_G	MSE_B	NCD
AP	110.01	51.21	111.35	0.2842
API	506.39	236.89	516.68	0.3869
BI	3804.12	1775.17	3849.09	0.8433
BD	408.78	180.29	413.30	0.4237
C2D2	319.33	553.62	326.10	0.3440
EMI	970.77	319.45	916.57	0.3682
MFI	984.47	135.13	997.33	0.4332
Proposed	78.06	78.58	78.05	0.2281

TABLE III
COMPARISON OF THE METHODS USING THE TRAIN IMAGE

Method	MSE_R	MSE_G	MSE_B	NCD
AP	44.43	30.80	78.39	0.0560
API	109.24	96.62	145.01	0.0776
BI	517.71	254.59	607.19	0.1450
BD	74.71	65.45	113.47	0.0744
C2D2	93.30	113.51	128.97	0.0702
EMI	159.42	152.53	195.69	0.0845
MFI	115.44	46.03	163.34	0.0798
Proposed	40.44	31.24	71.69	0.0503

TABLE II
COMPARISON OF THE METHODS USING THE PARROTS IMAGE

Method	MSE_R	MSE_G	MSE_B	NCD
AP	4.58	3.80	8.151	0.0167
API	5.40	4.28	7.895	0.0173
BI	34.85	14.93	38.251	0.0262
BD	4.87	4.05	8.415	0.0170
C2D2	5.44	5.24	7.099	0.0162
EMI	20.34	17.69	10.553	0.0207
MFI	7.09	2.90	10.433	0.0172
Proposed	3.90	2.49	6.261	0.0152

TABLE IV
AVERAGED RESULTS RELATED TO THE COLOR IMAGES SHOWN IN FIG. 6.

Method	MSE_R	MSE_G	MSE_B	NCD
AP	42.07	21.93	39.91	0.0532
API	51.78	32.54	50.26	0.0580
BI	154.12	72.11	159.33	0.0883
BD	44.19	27.27	45.79	0.0570
C2D2	44.10	34.85	45.75	0.0537
EMI	91.48	47.95	69.97	0.0649
MFI	56.30	22.56	58.27	0.0586
Proposed	36.55	18.87	35.80	0.0480

characterized by i. Since the original Bayer image is usually unavailable researchers resort to the approach of (16) in order to obtain test Bayer image data used for the CFA interpolation comparative evaluation [6],[7].

The efficiency of the interpolation methods is measured, objectively, via the mean square error (MSE) and the normalized color difference (NCD) criterion [3]. The MSE measure, which allows the evaluation in the RGB domain, is defined as follows:

$$MSE_k = \frac{1}{K_1 K_2} \sum_{i=1}^{K_1 K_2} \left(o_{ik} - y_{ik} \right)^2 \text{, for } k = 1,2,3 \qquad (17)$$

where $\mathbf{o}_i = (o_{i1}, o_{i2}, o_{i3})$ is the original pixel, $\mathbf{y}_i = (y_{i1}, y_{i2}, y_{i3})$ is the restored pixel, i denotes the pixel position in a $K_1 \times K_2$ color image and k characterizes the color channel.

The NCD criterion quantifies the perceptual similarity between the original and the obtained solution:

$$NCD = \frac{\sum_{i=1}^{K_1 K_2} \sqrt{\left(L_{\mathbf{o}_i} - L_{\mathbf{y}_i} \right)^2 + \left(u_{\mathbf{o}_i} - u_{\mathbf{y}_i} \right)^2 + \left(v_{\mathbf{o}_i} - v_{\mathbf{y}_i} \right)^2}}{\sum_{i=1}^{K_1 K_2} \sqrt{\left(L_{\mathbf{o}_i} \right)^2 + \left(u_{\mathbf{o}_i} \right)^2 + \left(v_{\mathbf{o}_i} \right)^2}} \qquad (18)$$

where L represents lightness values and u, v chrominance values corresponding to $\mathbf{o}_i$ and restored $\mathbf{y}_i$ samples expressed in CIELUV color space [3].

The enlarged outputs are obtained using the proposed CFA interpolation approach. Corresponding results are compared with of those achieved using such as bilinear interpolation (BI) [8], bilinear difference (BD) approach [6], alternating projections (AP) approach [7], color correlation-directional derivatives

method (C2D2) [4], median filter interpolation (MFI) [9], high definition color interpolation scheme (EMI) [10] and adaptive color plane interpolation (API) [11], respectively.

Table I summarizes the results obtained using the artificial CZP image shown in Fig. 5a. It can be seen that the AP scheme and especially the proposed method produce the best results among the tested methods. Applying the methods to the real-life images such as Parrots and Train, the proposed method clearly outperforms others CFA interpolation schemes, as is shown in Table II and Table III.

Table IV summarizes the results corresponding to the image database shown in Fig. 6. Using 20 color images, which vary in color and complexity, the robustness of the methods is examined here. The corresponding averaged results clearly indicate that the proposed method is robust and efficient, improves the image restoration process in terms of objective image quality measures and provides restored image which are impressively similar to the original.

Fig. 7 allows the visual (subjective) evaluation of the methods via the zoomed parts of the restored images. It can be seen that many demosaicing approaches (Fig. 7b-f) result in color artifacts and produce blurred edges. This inaccuracy in estimates is significantly reduced interpolating the images with the proposed scheme (Fig. 7g).

Summarizing the results presented above, the following conclusions can be stated: (i) the proposed method restores the color images in a sharp shape, (ii) the difference of the color appearance between the original image and the images restored by the proposed method is in unperceived form to humans, (iii) the proposed method achieves significant improvement in terms of objective (more than 20-30%) and subjective evaluation of the image quality than the state of-the-art CFA interpolation methods.
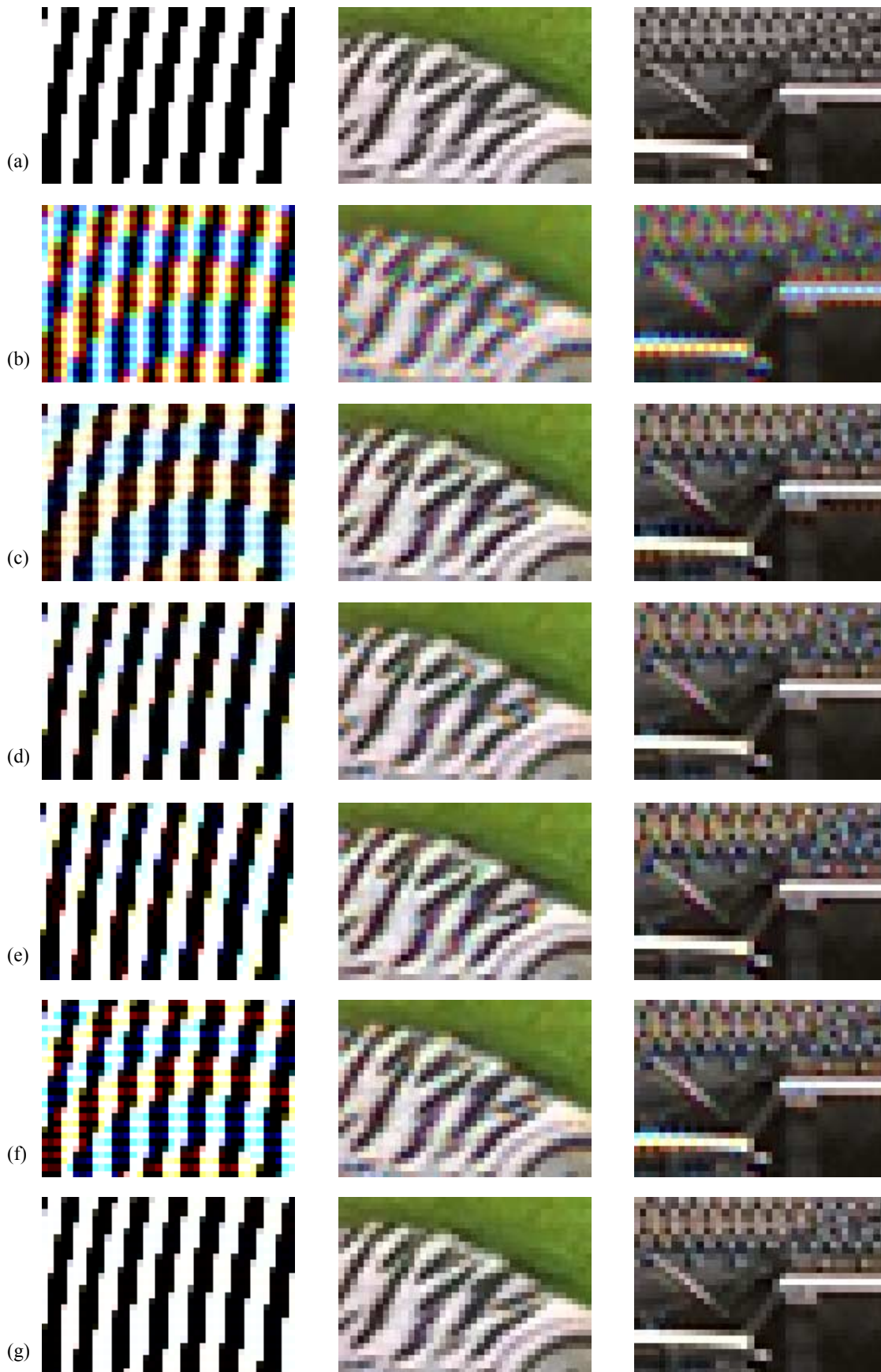
Fig. 7. Zoomed parts of the images corresponding to Fig. 5: (a) original images, (b) BI output, (c) BD output, (d) C2D2 output, (e) API output, (f) MFI output, (g) proposed method output.

V. CONCLUSION

A novel CFA interpolation approach was presented. The method employed an adaptive edge sensing mechanism, a color difference model and a correction step. Combining their advantages, the proposed method makes the interpolated images sharp, naturally colored and pleasurable for viewing. This also yields excellent results in terms of commonly used objective criteria. Simulation results and comparison reported here indicate that the introduced method is sufficiently robust and significantly outperforms the previously published approaches.

ACKNOWLEDGMENT

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