A NEW CFA INTERPOLATION TECHNIQUE FOR SINGLE-SENSOR DIGITAL CAMERAS

R. Lukac and K.N. Plataniotis

Bell Canada Multimedia Laboratory, The Edward S. Rogers Sr. Department of ECE,
University of Toronto, 10 King's College Road, Toronto, Canada
lukacr@ieee.org, kostas@dsp.utoronto.ca

ABSTRACT

A new color filter array (CFA) interpolation technique for single-sensor digital cameras is introduced. The proposed method utilizes an edge-sensing interpolation mechanism in conjunction with color-difference model based correction steps performed for each color channel. Thus, the proposed computationally efficient interpolation scheme is able to overcome the limitations of existing CFA based image acquisition solutions and restore color images without introducing false colors, edge blurring or visual artifacts. This produces excellent results in terms of subjective and objective image quality measures, while outperforming widely used CFA interpolation methods.

1. INTRODUCTION

The advances in color image processing [12] 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 [8] 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. 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. The Bayer pattern (*Fig.1*) [2], a widely used CFA, provides the array or mosaic of the RGB colors so that only one color element is available in each pixel. Two missing colors must be estimated from the adjacent pixels; this process refers to CFA interpolation, or demosaicing [4],[9].

2. PROBLEM FORMULATION

Let us consider, a $K_1 \times K_2$ gray-scale image $z : Z^2 \rightarrow Z$ representing a two-dimensional matrix of integer samples.

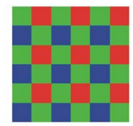

Fig. 1. Bayer color filter array.

In the Bayer CFA pattern, half of the pixels $z_i \in Z^2$, for $i = 1, 2, ..., K_1K_2$, correspond to the G channel, whereas R,B channels are assigned the other half of the pixels. Assuming that $p = 1, 2, ..., K_1$ and $q = 1, 2, ..., K_2$ 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 $\mathbf{x}_i = (x_{i1}, x_{i2}, x_{i3}) \in Z^2$, for $i = (p-1)K_2 + q$, as follows [10]:

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

This transformation forms a $K_1 \times K_2$ RGB image $\mathbf{x} : Z^2 \rightarrow Z^3$ representing a two-dimensional matrix of three-component samples [8]. 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. Therefore, it is desirable to estimate the missing color components of $\mathbf{x}$ and constitute the interpolated RGB image $\mathbf{y} : Z^2 \rightarrow Z^3$ to be as close to the desired RGB image $\mathbf{o} : Z^2 \rightarrow Z^3$ as possible. This problem can be expressed through the minimization of the expected value of mean square error as follows [13]:

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

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

To estimate the missing color components of $\mathbf{x}$, a sliding supporting window $W = \{\mathbf{x}_i \in Z^2; i = 0, 1, ..., N-1\}$ of finite size N is considered with the sample under consideration, sample $\mathbf{x}_0$, placed in the center of the window (*Fig.2a*). The procedure replaces the center $\mathbf{x}_0$ by some function of the local neighborhood area $\{\mathbf{x}_1, \mathbf{x}_2, ..., \mathbf{x}_{N-1}\}$

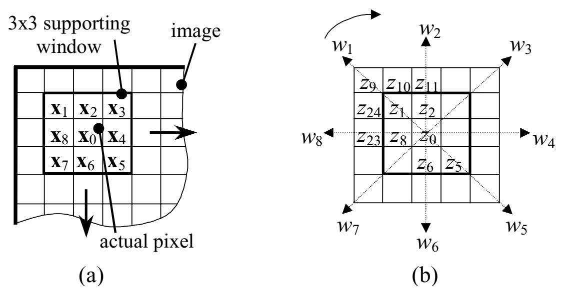

Fig. 2. Utilized components: (a) sliding supporting window, (b) edge-sensing weighting coefficients.

at a time. The rationale of this approach is to minimize the local distortion and ensure the stationarity of the processes generating the image [8].

3. PROPOSED METHOD

To follow structural information and interpolate missing image components in sharp shapes, efficient interpolation algorithms incorporate edge information into the interpolation process. The proposed method utilizes the edge-sensing mechanism of the C2D2 scheme [7]:

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

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

where w_1 and w_2 denote weights in north-west and north directions and $z_0, z_1, ..., z_{24}$ are original gray-scale values of z (*Fig.2b*). Coefficients w_3, w_5, w_7 and w_4, w_6, w_8 are calculated applying appropriately the concept of (3) and (4), respectively.

Using 8 weighting coefficients, the G channel is interpolated as follows:

$$\bar{y}_{02} = \begin{cases} x_{02} & \text{if } z_0 \cong x_{02} \\ \sum_{i=1}^{N-1} w'_i x'_{i2} & \text{otherwise} \end{cases} \quad (5)$$

where $N = 9$ relates to a 3×3 sliding window, z_0 is the acquired pixel before the transformation (1) in the same spatial position as the color (RGB) vector $\mathbf{x}_i$, operator $\cong$ denotes a one to one relationship and $w'_i = w_i / \sum_{j=1}^{N-1} w_j$ is the normalized weighting coefficient corresponding to predetermined G values x'_{i2}. For illustration purposes, quantities $x'_{(1)2}$ and $x'_{(2)2}$ are given by:

$$x'_{(1)2} = \left(x_{(2)2} + x_{(8)2}\right)/2 + ((z_1 - z_5)/(2\sqrt{2}) + (z_{11} - z_0 + z_{23} - z_0)/4)/2 \quad (6)$$

$$x'_{(2)2} = x_{(2)2} + (z_{11} - z_0 + z_2 - z_6)/4 \quad (7)$$

Using the difference plane model [1] and the G values obtained in (5), the R,B channels are estimated as follows:

$$\bar{y}_{0k} = \begin{cases} x_{0k} & \text{if } z_0 \cong x_{0k} \\ \bar{y}_{02} + f''_{(2i)k} & \text{if } z_0 \cong x_{02} \\ \bar{y}_{02} + f'''_{(2i-1)k} & \text{if } z_0 \cong x_{0(k\pm2)} \end{cases} \quad (8)$$

where $k = 1$ and $k = 3$ characterize the R and B channels, respectively; $f''_{(2i)k} = \sum_{i=1}^{(N-1)/2} w''_i (x_{(2i)k} - \bar{y}_{(2i)2})$ and $f'''_{(2i-1)k} = \sum_{i=1}^{(N-1)/2} w'''_i (x_{(2i-1)k} - \bar{y}_{(2i-1)2})$ are defined using normalized weights $w''_i = w_{2i} / \sum_{j=1}^{(N-1)/2} w_{2j}$ corresponding to edges in north, east, south and west directions; and coefficients $w'''_i = w_{(2i-1)} / \sum_{j=1}^{(N-1)/2} w_{(2j-1)}$ relate to diagonally positioned edges.

It has been observed [9] that introducing a correction mechanism into the interpolation process improves contrast and accuracy of the initially interpolated G channel. Since the difference plane model of (8) is simple and efficient, it is also perfectly suited to a correction stage. Thus, G values are corrected as follows [10]:

$$y_{02} = \begin{cases} \bar{y}_{0k} + g''_{(2i)k} & \text{if } z_0 \cong x_{0k} \\ \bar{y}_{02} & \text{otherwise} \end{cases} \quad (9)$$

where $g''_{(2i)k} = \sum_{i=1}^{(N-1)/2} w''_i (\bar{y}_{(2i)2} - \bar{y}_{(2i)k})$ is defined using the weighting coefficients w''_i of (8).

Considering the corrected G values of (9) the R,B update is completed using the proposed approach as follows:

$$y_{0k} = \begin{cases} y_{0k} & \text{if } z_0 \cong x_{0k} \\ y_{02} + h''_{(2i)k} & \text{if } z_0 \cong x_{02} \\ y_{02} + h'''_{(2i-1)k} & \text{if } z_0 \cong x_{0(k\pm2)} \end{cases} \quad (10)$$

where $h''_{(2i)k} = \sum_{i=1}^{(N-1)/2} w''_i (\bar{y}_{(2i)k} - y_{(2i)2})$, $h'''_{(2i-1)k} = \sum_{i=1}^{(N-1)/2} w'''_i (\bar{y}_{(2i-1)k} - y_{(2i-1)2})$ are defined using the weighting coefficients of (8), [10].

4. EXPERIMENTAL RESULTS

To examine the performance of the proposed framework and facilitate comparisons with the state of-the-art CFA interpolation schemes, some widely used natural test color images shown in *Fig.3* are utilized. All test images have been normalized to a standard size of 512×512 pixels with a 8-bit per channel RGB representation.

The proposed method is compared with other CFA interpolation methods listed in *Table 1*. To measure similarity between the original, full RGB, image $\mathbf{o}$ and interpolated image $\mathbf{y}$, a number of different objective measures, based on the difference in the statistical distributions of the pixel values, can be utilized [12]. In this paper, the mean square

Fig. 3. Test color images: (a) Parrots, (b) Window, (c) Train.

Table 1. Methods taken for comparison with the proposed method.

Abbr.	Method	Ref.
AP	Alternating projection approach	[4]
API	Adaptive color plane interpolation	[5]
BI	Bilinear interpolation	[11]
BD	Bilinear difference interpolation	[11]
C2D2	Color correlation-directional derivatives	[7]
EMI	Edge map interpolation	[6]
MFI	Median filter interpolation	[3]

error (MSE) and the normalized color difference (NCD) are used to measure objectively the quality of the restored RGB image.

Tables 2-4 summarize results corresponding to the restoration of test images shown in *Fig.3*. Using natural test images we are able to compare performance of the methods in realistic applications, since in these images the correlation between the color channels vary significantly. It can be seen that the flexible design characteristics of the proposed method result in excellent performance as the reported error values indicate.

Figs.4-6 present zoomed parts of the restored images. These images allow for the comparison of the results corresponding to the fundamental BI and currently used API technique with those obtained through the proposed method in terms of a subjective (user-centered) evaluation. It is evident that the BI scheme fails near edges and produces color artifacts. The API scheme produces more quality results. However, the proposed method is capable of restoring the color images with the highest visual quality among the tested schemes and avoids color shifts and visual artifacts. This results in impressive visual quality of the restored images.

5. CONCLUSIONS

A new CFA interpolation approach for single-sensor digital cameras was provided. The proposed edge-sensing method utilizes interpolation and correction steps based on a refined color difference model. Excellent design characteristics of the proposed method result in interpolated images which are sharp, naturally colored and pleasurable for viewing. Moreover, the new method outperforms previously developed interpolation methods in terms of commonly used objective criteria as well as the subjective evaluation.

Table 2. Comparison of the presented algorithms using the test image Parrots.

Method	MSE_R	MSE_G	MSE_B	*NCD*
AP	4.588	3.806	8.151	0.0167
API	5.403	4.285	7.895	0.0173
BI	34.858	14.935	38.251	0.0262
BD	4.876	4.059	8.415	0.0170
C2D2	5.446	5.242	7.099	0.0162
EMI	20.344	17.696	10.553	0.0207
MFI	7.090	2.909	10.433	0.0172
Proposed	3.909	2.490	6.261	0.0152

Table 3. Comparison of the presented algorithms using the test image Window.

Method	MSE_R	MSE_G	MSE_B	*NCD*
AP	6.16	3.38	6.61	0.0212
API	7.03	4.53	7.11	0.0209
BI	41.48	17.24	41.61	0.0417
BD	7.06	4.57	7.92	0.0228
C2D2	6.19	5.67	6.70	0.0193
EMI	12.42	9.80	11.33	0.0252
MFI	9.50	2.88	9.78	0.0239
Proposed	4.88	2.27	5.52	0.0181

6. REFERENCES

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Table 4. Comparison of the presented algorithms using the test image Train.

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

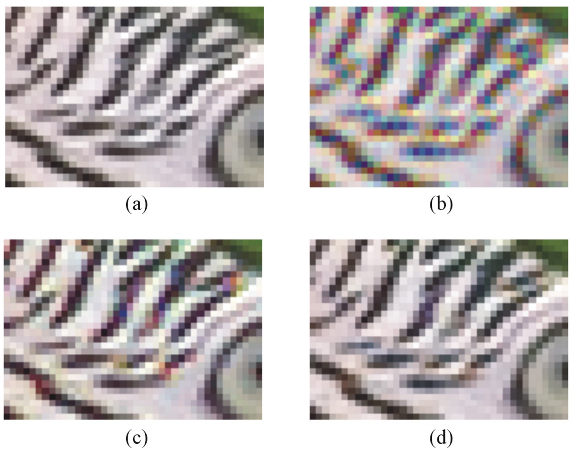

Fig. 4. Zoomed parts of the test image Parrots: (a) original image, (b) BI, (c) API, (d) proposed method.

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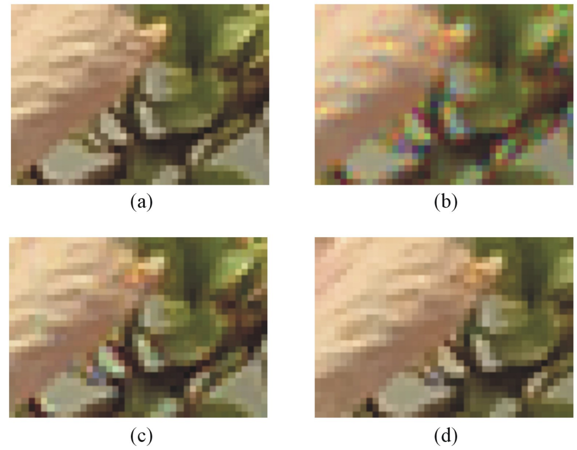

Fig. 5. Zoomed parts of the test image Window: (a) original image, (b) BI, (c) API, (d) proposed method.

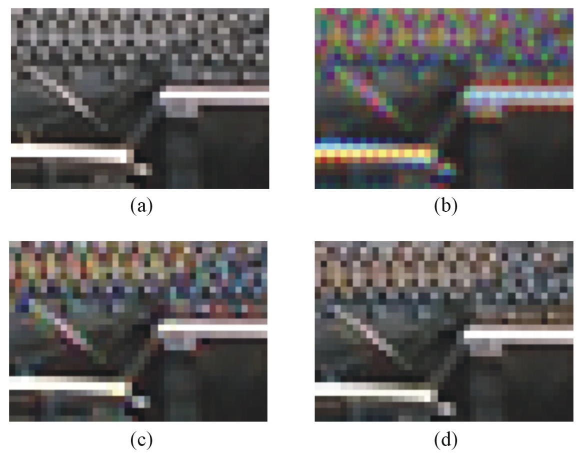

Fig. 6. Zoomed parts of the test image Train: (a) original image, (b) BI, (c) API, (d) proposed method.

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