Camera Image Processing System for Bayer CFA Based Imaging Devices

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Abstract—This paper focuses on a camera image processing system suitable for cost-effective single-sensor imaging devices such as image-enabled wireless phones and pocket-size imaging devices. The color filter array (CFA) zooming, CFA interpolation and CFA based postprocessing steps, employed in the proposed system, are unified to use a simple linear interpolator defined over the Bayer CFA components. Using the spectral correlation characteristics expressed through the differences between the available color components, the proposed system eliminates color artifacts in the enlarged, full color camera output.

I. INTRODUCTION

Cost-effective imaging devices use a single charge coupled device (CCD) or a complementary metal oxide semiconductor (CMOS) sensor with a color filter array (CFA) to produce a two-dimensional array or mosaic of color components. Such a CFA image is a low-resolution color image due to the fact that only a single spectral component is available at each spatial location. Using the Red-Green-Blue (RGB) Bayer CFA pattern (Fig. 1a) [3], the restored, high-resolution RGB color image output is obtained by interpolating the missing color components from the spatially adjacent CFA data. This process is known as CFA interpolation or demosaicking [5][8][9][13], and is an integral part of cost-effective single-sensor devices such as image-enabled wireless phones, pocket-size imaging devices and imaging devices for surveillance and automotive applications.

Devices such as mobile phones and personal digital assistants are restricted in their optical capabilities and computational resources [10]. To improve quality of the output, we unify CFA zooming, CFA interpolation and CFA based postprocessing procedures into a camera image processing system, similarly to the one introduced in [10]. However, to provide a computationally efficient approach the proposed method utilizes a simple linear interpolator instead of the nonlinear processing steps used in [10]. The additional simplification relates to the use of the spectral correlation characteristics expressed here in the form of the color-differences between the individual color components. Please note that the use of spectral models significantly decreases the amount of color artifacts in the camera output. To this end, instead of the color-ratio model used in [10], the proposed method uses the color-difference model of [1] which is easier to implement [13].

The aforementioned features make the proposed camera image processing system an attractive proposition which can be easily implemented in existing single-sensor imaging pipelines.

II. PROPOSED SINGLE-SENSOR IMAGING SYSTEM

Let us consider a $K_1 \times K_2$ Bayer CFA image $b : Z^2 \to Z^3$ representing a two-dimensional matrix of three-component RGB vectors $b_{(m,n)} = \{b_{(m,n,1)}, b_{(m,n,2)}, b_{(m,n,3)}\}$ located in the spatial position $(m,n)$, for $m = 1, 2, ..., K_1$ and $n = 1, 2, ..., K_2$. Each vector $b_{(m,n)}$ contains only a single measurement $b_{(m,n,k)}$, for $k = 1, 2, 3$, and two zeros corresponding to the missing measurements. The R CFA components $b_{(m,n,1)}$ are located at (odd $m$, even $n$), B CFA components $b_{(m,n,2)}$ are located at (even $m$, odd $n$) and G CFA components $b_{(m,n,3)}$ correspond to the rest of spatial positions [9].

To enlarge the limited spatial resolution of the output captured by cost-effective devices, we use a zooming algorithm operating on the CFA inputs [2][10]. Following the approach of [10], the original CFA data are assigned unique positions (Fig. 1b) in a $\lambda K_1 \times \lambda K_2$ zoomed image $\mathbf{x}$. Assuming for simplicity a description a zooming factor $\lambda = 2$, the vector $\mathbf{x}_{(2m-1,2n)} = b_{(m,n)}$ corresponds to the R component for (odd $m$, even $n$), whereas $\mathbf{x}_{(2m,2n-1)} = b_{(m,n)}$ corresponds to the B component for (even $m$, odd $n$). For the rest of locations $(m,n)$ in the original Bayer CFA image $b$, the color vector $\mathbf{x}_{(2m-1,2n-1)} = b_{(m,n)}$ in the enlarged CFA image $\mathbf{x}$ corresponds to the G component.

Assuming that $(r,s)$, for $r = 1, 2, ..., \lambda K_1$ and $s = 1, 2, ..., \lambda K_2$, denotes the spatial position in the enlarged image $\mathbf{x}$, missing G components $\mathbf{x}_{(r,s)}$ of the enlarged Bayer image $\mathbf{x}$ are computed using a linear interpolator operating on the surrounding original G components $x_{(i,j)}$:

$$x_{(r,s)} = \text{mean}\{x_{(i,j)}\}_{(i,j) \in \zeta} \quad (1)$$

where $(r,s)$ is the location at the centre of the diamond-shaped structure (Fig. 1b) of the four original G components described as $\zeta = \{(r-2,s), (r,s-2), (r,s+2), (r+2,s)\}$. To complete the remaining missing G components of the enlarged CFA image, (1) is repeated with $(r,s)$ located at the centre of the square-shaped structure described via $\zeta = \{(r-1,s-1), (r-1,s+1), (r+1,s-1), (r+1,s+1)\}$, Fig. 1c.

To constitute the missing R (and B) components, the spectral correlation approach defined over the color difference quantities [1][11][12] is utilized. Since G components are not present in the same locations as the R (or B) components, adjacent surrounding G components with the identical shift on the image lattice are used to create the color-difference quantities. The missing R (or B) component is estimated.
using the color-difference R-G quantities corresponding to surrounding spatial locations described by $\zeta$.

Thus, the R components $x_{(r,s)}$ are obtained as follows:

$$x_{(r,s)} = x_{(r-1,s)} + \text{mean}_{(i,j) \in \zeta} \{x_{(i,j)} - x_{(i-1,j)}\}$$  \hspace{1cm} (2)

where $(r,s)$ is the center of the square-shaped structure $\zeta = \{(r-2,s-2), (r-2,s+2), (r+2,s-2), (r+2,s+2)\}$, as it is shown in Fig.1d. The adjacent interpolated G components $x_{(i,j-1)}$ are positioned one unit to the left compared to the original R component $x_{(r,s)}$. Since the operand denotes the average color-difference the missing R component $x_{(r,s)}$ is obtained through the addition of the normalizing G component $x_{(r,s-1)}$ positioned one unit to the left according to an interpolated location $(r,s)$. The remaining missing R components are generated with another repetition of (2) defined over a diamond-shaped structure $\zeta = \{(r-2,s), (r,s+2), (r,s+2), (r+2,s)\}$ shown in Fig.1e.

The B components $x_{(r,s)}$ are generated in a similar manner as follows:

$$x_{(r,s)} = x_{(r-1,s)} + \text{mean}_{(i,j) \in \zeta} \{x_{(i,j)} - x_{(i-1,j)}\}$$  \hspace{1cm} (3)

where $\zeta = \{(r-2,s-2), (r-2,s+2), (r+2,s-2), (r+2,s+2)\}$ denotes the positions of the original B components $x_{(i,j)}$ shown in Fig.1d. The color difference quantities are generated using the G components $x_{(r-1,s)}$ in each group, one unit downward compared to the locations of the original B components $x_{(i,j)}$. Following the spatial arrangements of the B components shown in Fig.1e, the remaining B components are generated via (3) with $\zeta = \{(r-2,s), (r,s+2), (r,s+2), (r+2,s)\}$. This step completes the enlarged CFA image which now contains a single component in each spatial location (Fig.1f).

To obtain a full color image, the proposed camera image processing system continues (Fig.2) by interpolating the missing color components of the enlarged CFA image. Using the same linear interpolator as in the CFA zooming procedure, the missings G components $x_{(r,s)}$ are obtained via (1) with the diamond-shaped $\zeta = \{(r-1,s), (r,s+1)\}$. The corresponding spatial patterns are depicted in Fig.2a.

Due to the availability of the fully populated G color plane, the R $(k=1)$ and B $(k=3)$ components $x_{(r,s)}$ are obtained using the spectral correlations (color-difference quantities) as follows (Figs.2b-c):

$$x_{(r,s)} = x_{(r,s)} + \text{mean}_{(i,j) \in \zeta} \{x_{(i,j,k)} - x_{(i,j)}\}$$  \hspace{1cm} (4)

The interpolator of (4) is identical to (2) and (3) except that the color-difference quantities are generated using G components $x_{(i,j)}$ corresponding to the same spatial position as the R $(k=1)$ or B $(k=3)$ components $x_{(r,s)}$ forming the square-shaped structure $\zeta = \{(r-1,s), (r-1,s+1)\}$. Similarly to (2) and (3), the normalizing G component $x_{(r,s)}$ is used to re-scale the operand (average color-difference) back to the intensity domain. The remaining missing R and B components are generated using (4) with the diamond-shaped structure $\zeta = \{(r-1,s), (r,s+1)\}$ shown in Fig.2c. Once this is completed, a full color image is obtained with each spatial location containing three color components.

Since the demosaicked images contain a number of visual artifacts due to the limitations of the CFA interpo-
Fig. 3. Graphical illustration of the individual postprocessing steps: (a) correction of the previously interpolated G components using G and R (or G and B) components, (b–c) correction of the previously interpolated R (or B) components using R and G (or B and G) components.

Fig. 4. 512 x 512 test color images: (a) Lighthouse, (b) Window.

TABLE I

<table>
<thead>
<tr>
<th>Image</th>
<th>Lighthouse</th>
<th>Window</th>
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<tr>
<td>Method</td>
<td>MAE</td>
<td>MSE</td>
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<td>LZ</td>
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<tr>
<td>CIZ</td>
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<td>318.7</td>
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<td>CRNUF</td>
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<td>284.8</td>
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<tr>
<td>Proposed</td>
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<td>294.3</td>
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</table>

III. EXPERIMENTAL RESULTS

To examine the performance of the proposed method and facilitate comparisons with other zooming methods, color images shown in Fig.4 are utilized. All test images have been captured using a three-sensor device and normalized to 8-bit per channel RGB representation and 512 x 512 spatial resolution. The evaluation procedure used in the paper requires to down-sample a \( \lambda K_1 \times \lambda K_2 \) original color image \( o \) to a \( K_1 \times K_2 \) color image \( o_b \). Following common practices in the research community, mosaic versions \( b \) of the images are created by discarding color information of \( o_b \) using a GRGR phased Bayer CFA filter (Fig.1a), [5],[10]. The proposed method is evaluated by applying it to \( b \). The enlarged camera output \( x \) with size \( \lambda K_1 \times \lambda K_2 \) obtained using the proposed scheme is compared to the zoomed images achieved by the color-ratio-based nonlinear unified framework (CRNUF) [10], the local CFA zooming (LZ) scheme [2] and the conventional color image zooming (CIZ) approach. The LZ scheme utilizes...

Fig. 5. Camera outputs obtained using the test image Window: (a) CIZ, (b) proposed method.
replication based local CFA zooming approach [2] followed by bilinear CFA interpolation [8], whereas CIZ approach utilizes bilinear CFA interpolation followed by bilinear image zooming [7] in the RGB color domain. Note that the adaptive schemes of [4],[6],[15] can be used to boost performance of the RGB domain based zooming solutions, these approaches are computationally demanding to be embedded in cost-effective single-sensor imaging devices and thus, they are not considered in this paper.

To objectively measure the difference between the original image $o$ and the camera output $x$, both of the identical spatial resolution, the following criteria are used: the mean absolute error (MAE), the mean square error (MSE) and the normalized color difference (NCD) criterion [14].

As it can be seen from visual results shown in Figs. 5-6 and the numerical results summarized in Table 1, the proposed method outperforms both LZ and CIZ approaches which result in various false colors and blurred edges. Although the CRNUF produces the sharpest outputs among the tested methods, the use of the proposed system results in the images with comparable visual quality. However, due to utilization of an edge-sensing mechanism the CRNUF performs almost three-times larger amount of normalized operations and thus, the proposed system is more suitable for cost-effective imaging devices, which are restricted in their computational resources.

**IV. CONCLUSIONS**

A cost-effective single-sensor camera image processing system operating on Bayer CFA data was introduced. The proposed method utilizes unified, in terms of processing operations, CFA zooming, CFA interpolation and CFA postprocessing steps. The utilization of the color-difference model in conjunction with the linear-type interpolator ensures simplicity and high-computational power of the approach. Thus, the proposed system can be effectively embedded in single-sensor imaging devices such as wireless phones, PDAs, and camera devices for surveillance and automotive applications. It can be concluded that the proposed camera image processing system exhibits an adequate performance, produces enlarged color images, and reduces the amount of spectral artifacts present in the output compared to the images obtained using previously developed LZ and CIZ schemes.

**REFERENCES**