COLOR DEMOSAICKING USING DIRECTION CATEGORIZATION

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ABSTRACT

We propose a novel color demosaicking algorithm using direction categorization. Each pixel is classified as vertical, horizontal or smooth before interpolation. The categorization is based on gradient change within same channel, color differences and neighbors categories, so it explores relationship between intra- and inter-color channels. Color artifacts in reconstructed images are significantly reduced because directions of interpolation across edges are greatly avoided. Experimental results show that our proposed algorithm has high PSNR and the visual quality of reconstructed images is also obviously improved.

Index Terms— Color interpolation, Categorization, CCD, Bayer Pattern, Digital cameras

1. INTRODUCTION

Digital cameras are widely used as image capture devices nowadays. It is desirable to have three charge-coupled devices (CCD) to capture digital images with red (R), green (G) and blue (B) colors. Instead of using three CCD, one CCD with Bayer color filter array (CFA) (as shown in Fig.1) is usually used in order to reduce the production cost. As such only one color component is captured at every pixel. The process of reconstructing full color images (with three colors at every pixel) from such capturing images is called demosaicking or color interpolation.

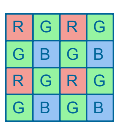

Fig. 1. Bayer Color Filter Array Pattern

Bilinear interpolation is a simple demosaicking method, but its reconstructed images are blurred and many color artifacts are induced. Thus, many demosaicking approaches are proposed to improve the quality of reconstructed images. Covariance-based adaptation edge-directed interpolation was proposed in [1]. Based on the property that color differences K_R $(G-R)$ and K_B $(G-B)$ are usually flat within small regions, Pei and Tam proposed to perform interpolation in K_R and K_B space instead of solely R, G and B space [2]. Wu and Zhang proposed a primary-consistent soft-decision color demosaicking (PCSD) to maintain the direction consistency among colors for each pixel [3]. In this paper, we propose a novel algorithm which classifies direction for interpolation at each pixel based on differences of same color channel, differences of inter-color channel and neighboring interpolation direction. These information consolidates the process of selecting correct directions before interpolation.

2. DEMOSAICKING PROCESS

In our proposed method, each pixel will be categorized as vertical (V), horizontal (H) or smooth (S) as direction for interpolation and their corresponding ways of interpolation are different. Our interpolation is performed in color difference space (K_R and K_B) which obtains reasonable results as shown in [2]. We firstly interpolate G elements at R and B pixels due to its highest sampling frequency in Bayer CFA. That is, we firstly obtain K_R and K_B at R and B pixels respectively. K_R and K_B are then interpolated in other pixels. R, G and B finally be reconstructed using K_R and K_B in the whole image. The following is the details of each procedure.

2.1. Categorization at red (R) and blue (B) pixels

For the categorization process, some pixels will be firstly classified as V, H, S in confident measurements. Based on categories of neighborhood, some more of the remaining pixels will be classified as V and H. Final categorization process based on color differences of neighbors will be performed at all the other pixels. In order to have more accurate categorization, refinement process will be performed afterward. Details are explained in the following subsections.

2.1.1. Confident measurements for vertical (V) and horizontal (H)

From the view of intra-channel, gradient change is a characteristic showing if there is edge. We therefore consider the

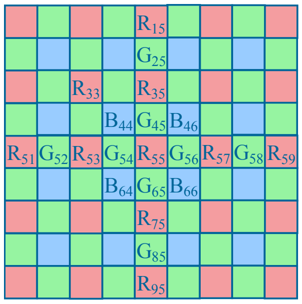

Fig. 2. Example of Bayer CFA with notation

vertical and horizontal gradients as a measure to determine if the pixel is along vertical or horizontal direction. Referring to Fig.2, vertical ($Grad^V$) and horizontal ($Grad^H$) gradient at R_{55} are calculated by

$$Grad^V = |R_{35} - R_{55}| + |G_{45} - G_{65}| + |R_{55} - R_{75}|$$
$$Grad^H = |R_{53} - R_{55}| + |G_{54} - G_{56}| + |R_{55} - R_{57}|$$

It is more likely that the pixel is along the direction which has smaller gradient change. If the difference between vertical and horizontal gradient is large enough, it shows confident that the pixel is along a direction. Thus, pixels are classified as V or H if their gradients satisfy following requirements,

$$V\text{: } (Grad^V < Grad^H) \text{ and } (|Grad^V - Grad^H| < T_{grad})$$
$$H\text{: } (Grad^H < Grad^V) \text{ and } (|Grad^H - Grad^V| < T_{grad})$$

where T_{grad} is a predefined threshold. Larger value of T_{grad} will ease the requirement of classifying pixels to be V or H.

Notice that pixels may not be classified at the moment if they are not satisfied the above requirements. Above example is to categorize V and H at R pixels. Pixels at G and B are also categorized similarly using the above method.

At this point, we make remarks on pixels which show strong confident on their categories so that they will not be refined in later processes. For example, R_{55} shows high confident of V if R_{55} and more than seven neighbors among $\{B_{44}, G_{45}, B_{46}, G_{54}, G_{56}, B_{64}, G_{65}, B_{66}\}$ are categorized as V. Pixels with high confident of H is also made remarks.

In order to keep consistency along edge, refinements are made on pixels that have ambiguous situation. For example, if R_{55} is H, but $\{G_{54}, G_{56}\}$ or $\{R_{53}, R_{57}\}$ are V, category of R_{55} is refined to V. Similarly, if R_{55} is V, but $\{G_{45}, G_{65}\}$ or $\{R_{35}, R_{75}\}$ are H, categorization of R_{55} is refined to H.

After this procedure, some pixels at R and B are categorized as V and H if they fulfill corresponding requirements.

2.1.2. Further categorization of vertical (V) and horizontal (H) using neighbors categories

We make use of neighbors categories to classify pixels without category because edges usually continue along pixels that gives relationship between neighbors pixels. There are three conditions that we can classify a pixel.

1. Pixel will be classified as V if its top and bottom nearest pixels of same channel are in V category. For example, if $\{R_{35}, R_{75}\}$ are V, R_{55} will be classified as V.
2. Pixel will be classified as H if its left and right nearest pixels of same channel are in H category. For example, if $\{R_{53}, R_{57}\}$ are H, R_{55} will also be classified as H.
3. Pixel will be classified as the same category if its top left, top right, bottom left and bottom right neighbors are in the same category. For example, if $\{B_{44}, B_{46}, B_{64}, B_{66}\}$ are all in H, we classify R_{55} as H too.

2.1.3. Confident measurements for smooth (S)

For R and B pixel locations which have not been categorized as V or H, color differences K_R $(G-R)$ at R and K_B $(G-B)$ at B are calculated vertically and horizontally for later categorization. Referring to Fig.2, suppose R_{55} has not been categorized yet, K^V_{R55} and K^H_{R55} are calculated by

$$\begin{aligned} K^V_{R55} =& \frac{1}{8}(G_{25} + 3G_{45} + 3G_{65} + G_{85}) \\ &- \frac{1}{16}(R_{15} + 4R_{35} + 6R_{55} + 4R_{75} + R_{95}) \quad (1) \\ K^H_{R55} =& \frac{1}{8}(G_{52} + 3G_{54} + 3G_{56} + G_{58}) \\ &- \frac{1}{16}(R_{51} + 4R_{53} + 6R_{55} + 4R_{57} + R_{59}) \quad (2) \end{aligned}$$

The above filters is different from that used in [2] because we observe that K_R or K_B is more accurate if we give more weight to neighbor pixels which is closer to the target pixel.

For pixels without categories, they are classified as S if

$$S\text{: } \begin{cases} |K^V_R - K^H_R| < T_K & \text{at } \quad R \text{ pixel} \\ |K^V_B - K^H_B| < T_K & \text{at } \quad B \text{ pixel} \end{cases} \quad (3)$$

where T_K is a predefined threshold. Larger value of T_K will ease the requirement of classifying pixel to be S.

2.1.4. Further categorization of vertical (V) and horizontal (H) using neighbors K_R and K_B

In this section, we describe a procedure that classify remaining R and B pixels without categories using their neighbors K_R and K_B respectively. We take Fig.2 as an example to classify R_{55} which is supposed that has not been categorized yet.

$\{K^V_{R55}, K^H_{R55}\}$ are computed in section 2.1.3 if R_{55} is without category. In this section, the K^V_{R55}, K^H_{R55} are used to compare with the K_R of their nearest top, bottom, left and right neighbors of same channel (R_{35}, R_{75}, R_{53}, R_{57}) for determining the category of R_{55}. We take into account only the neighbors with category and then calculate the neighbors K_R corresponding to their category. If neighbors category are V or H, using method described in equation (1) and (2) to compute K_R. If the neighbors category is S, the corresponding K_R^S is simply average of its $\{K_R^V, K_R^H\}$. After calculating neighbors K_R, we compute the sum of differences of them with K_{R55}^V and with K_{R55}^H respectively. That is,

$$
\begin{aligned}
Diff_{K_{R55}^V} =& |K_{R55}^V - K_{R35}| + |K_{R55}^V - K_{R75}| \\
&+ |K_{R55}^V - K_{R53}| + |K_{R55}^V - K_{R57}| \quad (4)\\
Diff_{K_{R55}^H} =& |K_{R55}^H - K_{R35}| + |K_{R55}^H - K_{R75}| \\
&+ |K_{R55}^H - K_{R53}| + |K_{R55}^H - K_{R57}| \quad (5)
\end{aligned}
$$

Notice that if there is neighbor without category, the neighbor K_R does not exist. So the difference compare to that neighbor is not consider and set to zero. Suppose R_{57}, for instance, does not have category yet, the $|K_{R55}^V - K_{R57}|$ in equation (4) is set to zero when calculating $Diff_{K_{R55}^V}$.

As we observe that more categorized neighbors provide more information to assist to compute the difference for categorization, we firstly classify remaining uncategorized pixels with three or more categorized neighbors, then classify remaining pixels. After obtaining the two sum of differences, categorize the pixel by

$$
\begin{aligned}
V&: \quad Diff_{K_R^V} <= Diff_{K_R^H}\\
H&: \quad Diff_{K_R^H} < Diff_{K_R^V}
\end{aligned}
$$

2.1.5. Refinement on ambiguous condition

Although all R and B pixels are categorized, there may be some ambiguous situation when considering their neighbors categories. We make pixels with ambiguous situation uncategorized and then categorize them again. There are three ambiguous conditions for pixels.

1. Pixel is classified as H, but the left and right nearest pixels of same channel are in V category. For example, suppose R_{55} is classified as H, but $\{R_{53}, R_{57}\}$ are V.
2. Pixel is classified as V, but the top and bottom nearest pixels of same channel are in H category, For example, suppose R_{55} is classified as V, but $\{R_{35}, R_{75}\}$ are H.
3. Pixel is classified as a category which is different from category that all the neighbors of top left, top right, bottom left and bottom right belong to. For example, suppose R_{55} is classified as V, but $\{B_{44}, B_{46}, B_{64}, B_{66}\}$ are all in the H category.

If pixel fulfills any one of the above condition and do not have high confident remark (mentioned in section 2.1.4), we make it uncategorized and then categorize them using method described in section 2.1.4.

We have categorize all pixels at R and B after this refinement process. We will then categorize pixels at G.

2.2. Categorization at green (G) pixels

Categories at G are simply based on their top, bottom, left, and right neighbors. Referring to Fig.2, categorizing G_{54} by considering categories of $\{top, bottom\}$ neighbors ($\{B_{44}, B_{64}\}$) and $\{left, right\}$ neighbors ($\{R_{53}, R_{55}\}$) as follows,

V: $\{top, bottom\}$ neighbors are in V
H: $\{left, right\}$ neighbors are in H

If G_{54} satisfies both conditions or does not satisfy any condition, it is classified as S which takes balance of V and H.

After this procedure, all pixels have their categories.

2.3. Interpolation of K_R and K_B

We firstly interpolate K_R at R and K_B at B according to their categories. Then using the calculated K_R and K_B to interpolate K_R at B and K_B at R. With the aid of calculated K_R and K_B, K_R and K_B at G is finally obtained. We describe only the process of interpolation of K_R in the following because interpolation of K_B is the same by interchanging R and B in the procedures. We use Fig.2 as an example in the following.

2.3.1. Interpolation of $K_R(K_B)$ at $R(B)$

Calculating K_{R55} (K_R at R_{55}) according to its category by

V: use equation (1)
H: use equation (2)
S: average K_{R55}^V in equation (1) and K_{R55}^H in equation (2)

2.3.2. Interpolation of $K_R(K_B)$ at $B(R)$

Calculating K_{R44} (K_R at B_{44}) with the aid of K_R at R by

$$K_{R44} = \frac{1}{4}(K_{R33} + K_{R35} + K_{R53} + K_{R55})$$

2.3.3. Interpolation of $K_R(K_B)$ at G

Calculating K_{R54} (K_R at G_{54}) according to its category by

$$
\begin{aligned}
V&: \quad \frac{1}{2}(K_{R44} + K_{R64})\\
H&: \quad \frac{1}{2}(K_{R53} + K_{R55})\\
S&: \quad \frac{1}{4}(K_{R44} + K_{R53} + K_{R55} + K_{R64})
\end{aligned}
$$

2.4. Reconstruction of red (R), green (G) and blue (B)

After obtaining K_R and K_B at all pixels, we reconstruct R, G and B.

At R pixel: $G' = K_R + R$, $B' = G' - K_B$
At G pixel: $R' = G - K_R$, $B' = G - K_B$
At B pixel: $G' = K_B + B$, $R' = G' - K_R$

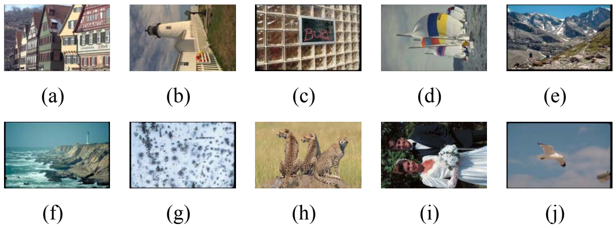

Fig. 3. Image set for experiment

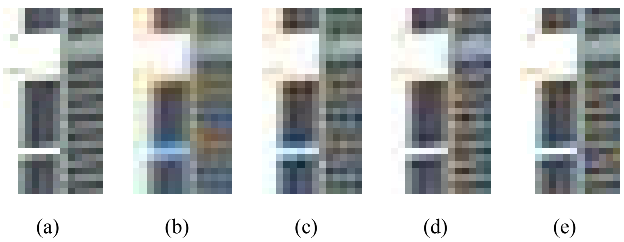

Fig. 4. Zoomed part of reconstructed image Fig.3(a) from (a) original, (b) bilinear, (c) SC, (d) PCSD, (f) proposed method

3. EXPERIMENTAL RESULTS

Our proposed method is compared with bilinear and methods proposed in [2] and [3] using image set shown in Fig.3. The images are initially filtered by Bayer CFA and then are applied the demosaicking approaches. Peak-signal-to-noise ratio (PSNR) are computed as objective measurement for comparison. In our experiments, T_{grad} and T_K are set to 20 and 10. The results are shown in Table 1.

Bilinear interpolation is known as a simple method but with poor performance (see Table 1 and reconstructed images in Fig.4(b) and Fig.5(b)). The approach using signal correlation (SC) in [2] also performs interpolation in K_R and K_B space, but it does not consider direction of interpolation. Color artifacts are found at the edge of objects especially places with large variation of K_R or K_B. Primary consistent soft-decision (PCSD) [3] maintains direction consistency among colors, but when comparing to our proposed method, we are more adaptive to find edge in image and avoid interpolation across edges so that color artifacts are minimized. Better visual quality of reconstructed images using our method are easily noticed in Fig.4(e) and Fig.5(e). The average PSNR of reconstructed images applied by our proposed method is higher than that by PCSD about 2 dB and about 9 dB higher than that of bilinear interpolation.

4. CONCLUSION

A novel color demosaicking using direction categorization is presented in this paper. Categorization explores relationship within intra- and inter-channel so that interpolation across edges is greatly avoided. Our proposed algorithm has average PSNR 9 dB higher that of bilinear method and has obviously improvement in visual quality.

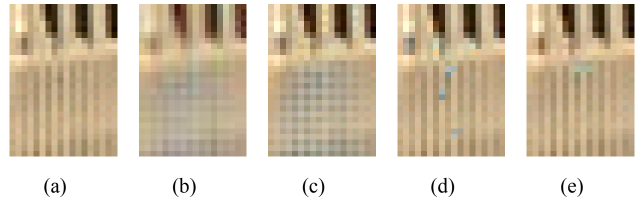

Fig. 5. Zoomed part of reconstructed image Fig.3(b) from (a) original, (b) bilinear, (c) SC, (d) PCSD, (f) proposed method

Method	Img	R	G	B	Img	R	G	B
(I)	(a)	22.5	27.4	22.7	(b)	27.0	31.8	27.1
(II)		30.2	33.1	29.8		34.5	37.1	34.3
(III)		32.3	34.7	31.6		37.1	39.3	37.0
(IV)		35.8	37.8	34.5		39.7	41.9	39.4
(I)	(c)	26.4	31.2	26.1	(d)	31.4	35.7	31.5
(II)		34.0	36.5	33.2		38.5	41.1	38.3
(III)		36.7	39.3	35.9		40.3	42.7	39.9
(IV)		38.4	41.7	37.4		42.0	44.9	41.4
(I)	(e)	24.7	28.7	25.3	(f)	27.6	32.7	29.1
(II)		32.5	34.8	32.6		34.3	38.7	36.2
(III)		32.2	34.5	32.2		34.8	38.8	36.5
(IV)		34.6	37.2	34.1		36.2	41.3	38.1
(I)	(g)	27.8	33.5	30.1	(h)	27.6	31.8	27.9
(II)		34.5	39.3	37.6		36.5	37.7	36.5
(III)		35.1	39.0	36.9		36.2	37.5	36.4
(IV)		37.1	41.7	38.3		37.8	39.6	37.1
(I)	(i)	28.8	32.3	29.5	(j)	35.9	40.5	34.8
(II)		36.0	38.3	36.8		40.7	44.6	40.5
(III)		35.6	38.0	36.0		42.0	45.8	43.0
(IV)		37.3	40.2	37.7		42.7	47.1	43.7

Table 1. Comparison of PSNR (in dB) between (I) bilinear, (II) SC[2], (III) PCSD[3] and (IV) proposed method

5. REFERENCES

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