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
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

\[
\begin{align*}
\text{Grad}^V &= |R_{35} - R_{55}| + |G_{45} - G_{65}| + |R_{55} - R_{75}| \\
\text{Grad}^H &= |R_{53} - R_{55}| + |G_{54} - G_{56}| + |R_{55} - R_{57}|
\end{align*}
\]

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,

\[
\begin{align*}
\text{V}: (\text{Grad}^V < \text{Grad}^H) \quad \text{and} \quad |(\text{Grad}^V - \text{Grad}^H| \leq T_{grad}) \\
\text{H}: (\text{Grad}^H < \text{Grad}^V) \quad \text{and} \quad |(\text{Grad}^H - \text{Grad}^V| < T_{grad})
\end{align*}
\]

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 categori-
ized 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 with-
out 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, \(K_V^{R_{55}}\) and \(K_H^{R_{55}}\) are calculated by

\[
\begin{align*}
K_V^{R_{55}} &= \frac{1}{8} (G_{25} + 3G_{45} + 3G_{65} + G_{85}) \\
&- \frac{1}{16} (R_{15} + 4R_{35} + 6R_{55} + 4R_{75} + R_{95}) \\
K_H^{R_{55}} &= \frac{1}{8} (G_{52} + 3G_{54} + 3G_{56} + G_{58}) \\
&- \frac{1}{16} (R_{51} + 4R_{53} + 6R_{55} + 4R_{57} + R_{69})
\end{align*}
\]

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

\[
S: \begin{cases}
|K_V^R - K_H^R| < T_K & \text{at } R \text{ pixel} \\
|K_B^H - K_H^B| < T_K & \text{at } B \text{ pixel}
\end{cases}
\]

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 remain-
ing \(R\) 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.

\(\{K_V^{R_{55}}, K_H^{R_{55}}\}\) are computed in section 2.1.3 if \(R_{55}\) is
without category. In this section, the \(K_V^{R_{55}}\) and \(K_H^{R_{55}}\) 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 $K_R$ is simply average of its $K^V_R$, $K^H_R$. After calculating neighbors $K_R$, we compute the sum of differences of them with $K^V_{R55}$ and with $K^H_{R55}$ respectively. That is,

$$Diff_{K^V_{R55}} = |K^V_{R55} - K_{R53}| + |K^V_{R55} - K_{R75}|$$

$$+ |K^V_{R55} - K_{R35}| + |K^V_{R55} - K_{R57}|$$

$$Diff_{K^H_{R55}} = |K^H_{R55} - K_{R53}| + |K^H_{R55} - K_{R75}|$$

$$+ |K^H_{R55} - K_{R35}| + |K^H_{R55} - K_{R57}|$$

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 $|K^V_{R55} - K_{R57}|$ in equation (4) is set to zero when calculating $Diff_{K^V_{R55}}$.

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

$$V: Diff_{K^V_R} <= Diff_{K^H_R}$$

$$H: Diff_{K^H_R} < Diff_{K^V_R}$$

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 $\{R_{35}, R_{75}\}$ 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,

$$V: \{top, bottom\} \text{ neighbors are in } V$$

$$H: \{left, right\} \text{ neighbors are in } H$$

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 $K_{R55}$ ($K_B$ at $R_{55}$) according to its category by

$$V: \text{ use equation (1)}$$

$$H: \text{ use equation (2)}$$

$$S: \text{ average of } K^V_{R55} \text{ in equation (1) and } K^H_{R55} \text{ in equation (2)}$$

2.3.2. Interpolation of $K_B(K_R)$ 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

$$V: \frac{1}{2}(K_{R44} + K_{R64})$$

$$H: \frac{1}{2}(K_{R53} + K_{R55})$$

$$S: \frac{1}{4}(K_{R44} + K_{R53} + K_{R55} + K_{R64})$$

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

5. REFERENCES

