Adaptive Guided Upsampling For Color Image Demosaicking

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***Abstract*—Color demosaicking is a significant step that enables digital cameras to recover full pixels from a raw image. In this paper, we propose an efficient color image demosaicking model based on guided upsampling. Guided upsampling using residual interpolation has been prominent in comparison to other methods. In the present study, we developed an adaptive guided upsampling method without RI. Our approach consists of adaptive guided upsampling and color-component difference interpolation. We utilize color difference interpolation and guided upsampling for its preprocessing in the G channel interpolation and interpolate the R and B channel with guided upsampling using recovered G channel. The results of the experiments prove that our approach is superior to RI-based methods on both objective and subjective performance for the Kodak and the IMAX datasets.**

***Index Terms*—Demosaicking, guided filter, Bayer color filter array, image processing.**

I. Introduction

On account of cost, most digital cameras employ a single image sensor with a color filter array (CFA). In color images, each pixel consists of multiple color components. RGB images, which are the most popular color image type, have red, green and blue bands in every pixel. However, a single image sensor can record only one color component in each pixel and CFA patterns decide the pattern of the mosaicked image. So, other color channels must be interpolated to reconstruct full color images based on CFA patterns. The Bayer CFA pattern [1], as shown in Fig.1 is the most common CFA design. Numerous approaches have been attempted for the Bayer pattern for a long time. The green channel is composed of half of the RAW image, which is the initial image. Therefore, most methods for the Bayer pattern try to recover the G channel firstly. Then, the red channel and the blue channel are interpolated by utilizing the reconstructed G channel. Consequently, the quality of the recovered green channel is a key for the whole demosaicking peformance.

Initially, color demosaicking methods were performed on each color channel independently because of the poor computation power in the past. However, there are spectral correlations in color images and a lack of spectral correlation produces color artifacts. Recently, plenty of techniques take advantage of spectral correlations to improve demosaicking performance. One of the major approaches is the color difference interpolation [2]–[5]. This strategy reflects spectral correlations exiting among the three color bands. The more spectral correlations the method elicits, the better the quality of the demosaicking. The color difference interpolation-based demosaicking approach starts with recovering the green component and interpolating the red and blue components. The color difference approach estimates the missing value using the color difference(i.e., between red and green).

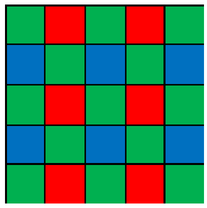
Fig. 1. The Bayer CFA pattern

Recently, the residual interpolation algorithms [6]–[9] have achieved good results. The residual interpolation-based methods combine guided upsampling and residual interpolation. The guide upsampling utilizes the other color component as the guide to reconstruct missing color components. The interpolation of the residual field between the initially acquired value and the value acquired by the guided upsampling improves the quality of the upsampling.

In this paper, we proposed a new guided upsampling technique for color image demosaicking. We analyzed the guided upsampling and the residual interpolation. Therefore, we realize why the guided upsampling without the residual interpolation is not efficient and how the problem can be solved in the guided upsampling. The experimental results demonstrate that our proposed demosaicking method performs well on both objective and subjective performance for the 24 Kodak images and the 18 IMAX images.

II. Adaptive Guided Upsampling For Demosaicking

First of all, we explain the basic theory of the proposed guided upsampling. Then we describe the interpolation of red pixel values as an example. The difference between our proposed algorithm and the residual interpolation is shown in Fig.2. Fig.2 also describes the process of the our proposed guided upsampling in a red band.

A. *Guided upsampling with residual interpolation*

The MLRI [9] upsamples the color components using the guided filter [10]. The guided filter is an edge-preserving filter and its computing time is fast. These features are suitable for demosaicking. The guided filter calculates the output from the two inputs which are the guidance image and the input image,

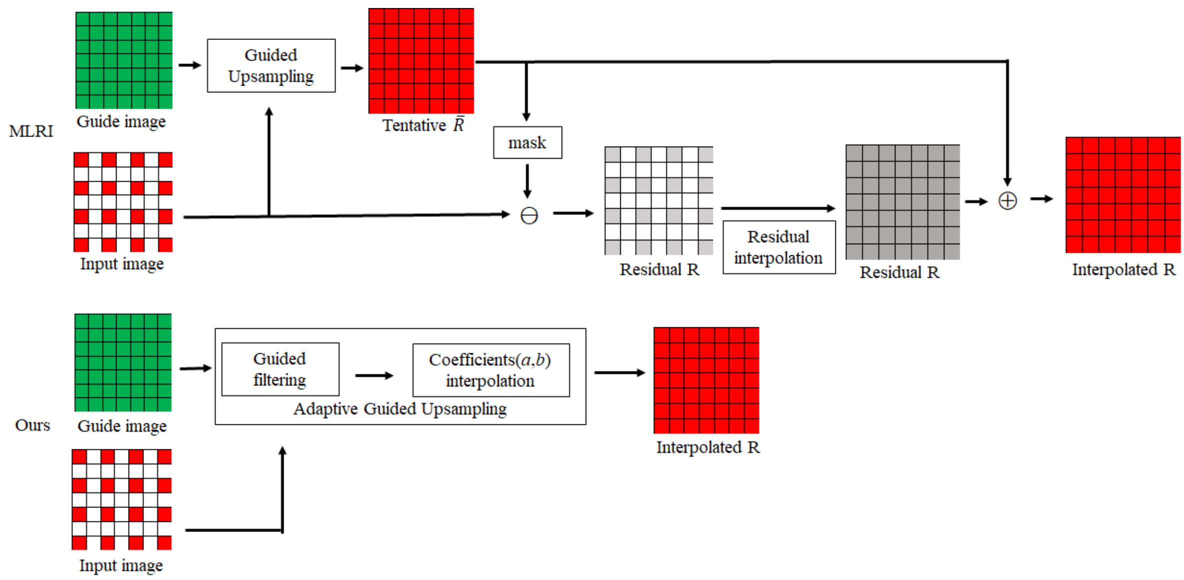

Fig. 2. Adaptive Guide Filter For Demosaicking

as shown in Fig.2. The guided filtering generates the tentative image in a local window $\boldsymbol{\omega_{p,q}}$ centered in the pixel $(\boldsymbol{p}, \boldsymbol{q})$ as

$$R_{i,j} = a_{p,q}G_{i,j} + b_{p,q} \tag{1}$$

$\boldsymbol{a_{p,q}}$ and $\boldsymbol{b_{p,q}}$ are the linear coefficients in $\boldsymbol{\omega_{p,q}}$. The guided filter usually subtracts the average of the value in the window from the value of each pixel in the window to remove the DC component, $\boldsymbol{b_{p,q}}$. However, the MLRI uses the Laplacian energy instead. The Laplacian energy is defined as

$$\Delta A = \begin{pmatrix} 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 4 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 \end{pmatrix} A$$

The MLRI calculates the $a_{p,q}$ by minimizing the following equation using the Laplacian energy.

$$\begin{aligned} E &= \sum_{i,j\in\omega_{p,q}} (M_{i,j}\Delta(R_{i,j} - \hat{R}_{i,j}))^2, \\ &= \sum_{i,j\in\omega_{p,q}} (M_{i,j}\Delta(R_{i,j} - a_{p,q}G_{i,j} - b_{p,q}))^2, \\ &= \sum_{i,j\in\omega_{p,q}} (M_{i,j}(\Delta R_{i,j} - a_{p,q}\Delta G_{i,j}))^2 \end{aligned} \tag{2}$$

$M_{i,j}$ is a binary mask and the DC component $b_{p,q}$ is calculated from (1). The MLRI introduces a weighted average of these linear coefficients instead of an average to change the patch based linear coefficients into pixel based linear coefficients. The weighted average is defined as

$$\hat{a}_{ij} = \frac{\sum_{p,q\in\omega_{i,j}} W_{p,q}a_{p,q}}{\sum_{p,q\in\omega_{i,j}} W_{p,q}}, \hat{b}_{ij} = \frac{\sum_{p,q\in\omega_{i,j}} W_{p,q}b_{p,q}}{\sum_{p,q\in\omega_{i,j}} W_{p,q}} \tag{3}$$

The weight is decided based on the residual cost as

$$W_{p,q} = 1/\frac{1}{|\omega_{p,q}|}\sum_{i,j}((R_{i,j} - a_{i,j}G_{i,j} - b_{i,j}))^2 \tag{4}$$

where, $|\omega_{p,q}|$ is the number of the pixels which the input image has the value in the window.

B. Adaptive Guided Upsampling

We analyzed the residual interpolation and learned the two reasons which make the residual interpolation effective in the guided upsampling. (i)Linear transform produces a gap in the DC component and the gap should be filled. (ii)The gain component, $\hat{a}_{p,q}$, which is calculated by the guided filtering and located in the missing pixel, is not reliable enough to recover the missing pixel well. (Fig.3) Therefore, we determined that the adaptive guided upsampling does not utilize the gain component $\hat{a}_{p,q}$ in the missing pixel and fill the gap of the DC component. In addition, we interpolate the unreliable coefficients that were located in missing pixels from the reliable coefficients.(Fig.3) After the linear transform of $\hat{a}_{p,q}$ is calculated, we defined $\hat{b}_{p,q}$ to get rid of the gap as

$$\hat{b}_{i,j} = R_{i,j} - M_{i,j}\hat{a}_{i,j}G_{i,j} \tag{5}$$

However, $\hat{b}_{p,q}$ can only be calculated in the pixels where the input image initially has values and $\hat{a}_{p,q}$ at the missing pixel should also be replaced. So, we introduced the coefficient interpolation (CI) to fill the missing coefficients. In III-A2, we simply used the bilinear interpolation to supply the missing coefficients and the normal guided filter strategy in (2). In the red and blue components' interpolation III-B, we installed the weighted average based on the color difference interpolation because the coefficients($\hat{a}_{p,q}$,$\hat{b}_{p,q}$) are the connections between the two color channels and we think the idea of color difference (some kind of connection between the two color channels) interpolation can be applied. There are three types of interpolation which are divided

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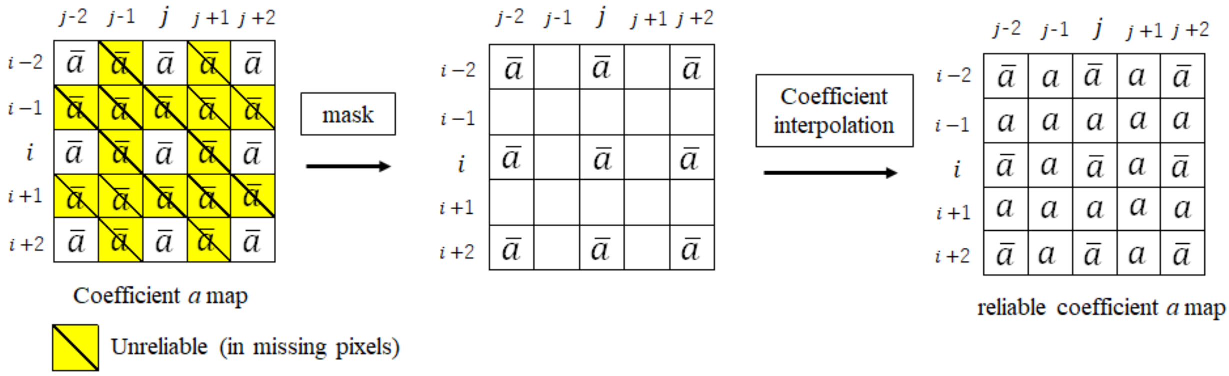


Fig. 3. coefficient interpolation

TABLE I
THE AVERAGE PSNRS AND CPSNRS OF THE IMAX 18 IMAGES AND THE KODAK 24 IMAGES

method	Kodak				IMAX				Kodak +IMAX			
	PSNR			CPSNR	PSNR			CPSNR	PSNR			CPSNR
	R	G	B		R	G	B		R	G	B	
GBTF [11]	**39.48**	**43.12**	**39.85**	**40.43**	33.54	36.57	32.72	33.92	36.93	40.31	36.79	37.64
FDRI [12]	37.29	39.10	37.14	37.69	36.92	40.17	35.54	36.99	37.13	39.56	36.46	37.39
RI [6]	37.90	40.95	37.79	38.58	36.07	39.96	35.35	36.48	37.12	40.53	36.74	37.68
MLRI [9]	38.74	41.18	38.57	39.20	36.72	40.23	35.59	36.91	37.88	40.77	37.29	38.22
ours	38.95	41.64	38.82	39.57	**36.94**	**40.40**	**35.76**	**37.11**	**38.09**	**41.11**	**37.51**	**38.52**

by where the target pixel is located.

$$\begin{aligned} a_{i,j} =&(\omega_N \bar{a}_{i-1,j} + \omega_S \bar{a}_{i+1,j})/(\omega_N + \omega_S) \\ a_{i,j} =&(\omega_W \bar{a}_{i,j-1} + \omega_E \bar{a}_{i,j+1})/(\omega_W + \omega_E) \\ a_{i,j} =&(\omega_N \bar{a}_{i-1,j} + \omega_S \bar{a}_{i+1,j} + \\ &\omega_W \bar{a}_{i,j-1} + \omega_E \bar{a}_{i,j+1})/\omega_t \\ \omega_t =&(\omega_N + \omega_S + \omega_W + \omega_E) \end{aligned} \tag{6}$$

We introduced a similar weight with (13).

$$\begin{aligned} \omega_E &= \sum_{a=i-1}^{i+1} \sum_{a=j}^{j+2} D^H_{a,b}, \omega_W = \sum_{a=i-1}^{i+1} \sum_{a=j-2}^{j} D^H_{a,b} \\ \omega_N &= \sum_{a=i-2}^{i} \sum_{a=j-1}^{j+1} D^V_{a,b}, \omega_S = \sum_{a=i}^{i+2} \sum_{a=j-1}^{j+1} D^V_{a,b} \end{aligned} \tag{7}$$

where $D^H_{a,b}$,$D^V_{a,b}$ is derived from (11) in the green interpolation. Finally, our adaptive guided upsampling interpolates the missing values using the guide image and the pixel-based coefficients($a_{i,j}, b_{i,j}$) as

$$R_{i,j} = a_{i,j} G_{i,j} + b_{i,j} \tag{8}$$

III. Proposed Algorithm

We proposed two new approaches for demosaicking.
(1) Adaptive guided upsampling (as shown in the previous section)
(2) Guided upsampling without the linear Laplacian filter
Now we will include an explanation of the second approach, which was used for guided upsampling of the green interpolation.

A. Green interpolation

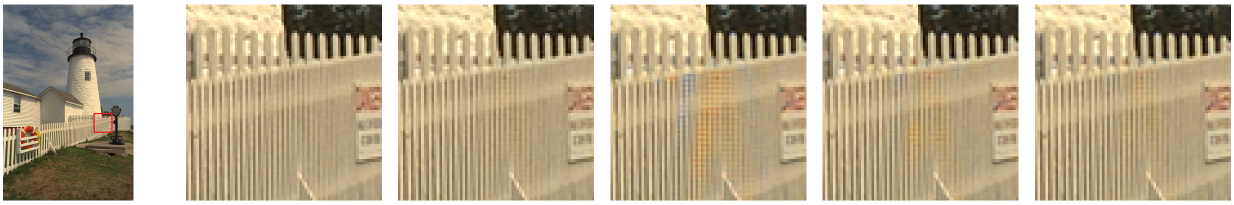
We incorporate our proposed guided upsampling with the GBTF algorithm [11] to recover the green channel. Our proposed green channel interpolation consists of three steps. (I) All channels are interpolated in the horizontal and vertical direction by the linear interpolation. (II) All channels are interpolated in the horizontal and vertical directions by the adaptive guided upsampling. (III) The green channel is interpolated by the GBTF-based color difference interpolation.

1) The linear interpolation: The linear formula for the green pixel can be expressed as

$$\begin{aligned} \hat{G}^H_{i,j-1} &= (G_{i,j-2} + G_{i,j})/2, \\ \hat{G}^V_{i-1,j} &= (G_{i-2,j} + G_{i,j})/2 \end{aligned} \tag{9}$$

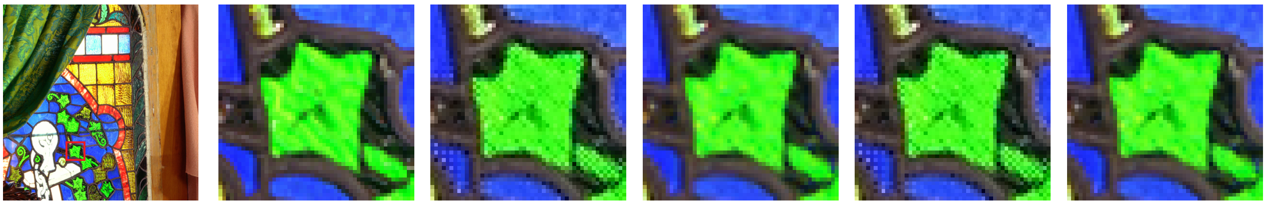
$\hat{G}^H$ means the horizontal interpolated green pixel and $\hat{G}^V$ means the vertical interpolated green pixel. We interpolated the red and blue pixels in the same process.

2) Guided upsampling: We execute the guided upsampling with the result of the linear interpolation. We recover the horizontal green component by using the horizontal blue and red components as its guide, and the horizontal blue and red components by using the horizontal green components as their guide. In this step, MLRI uses the linear Laplacian filter to obtain tentative linear images. However, we empirically learned that the normal Laplacian filter is not appropriate to calculate the tentative linear images because it reflects both vertical and



(a) Original (b) GBTF [11] (c) FDRI [12] (d) MLRI [9] (e) ours

Fig. 4. Visual comparison for the fence region of lighthouse in the Kodak dataset



(a) Original (b) GBTF [11] (c) FDRI [12] (d) MLRI [9] (e) ours

Fig. 5. Visual comparison for the fence region of the star in the IMAX dataset

horizontal components. Additionally, the linear Laplacian filter is inadequate because it disposes the DC component in three of nine pixels. (the size of a patch is (3×3)). Therefore, we decided to use a normal guided filter in order to exclude the DC component by subtracting the average of the patch from each pixel value in the patch.

3) Color difference interpolation: We perform the color difference interpolation based on the GBTF algorithm [11] using the tentative color values by the adaptive guided upsampling III-A2. In this step, the color difference for the horizontal and vertical directions is described as

$$\boldsymbol{\hat{\delta}^H} = \begin{cases} \boldsymbol{G^H - R^H} & (at\ Red\ pixel) \\ \boldsymbol{G^H - R^H} & (at\ Blue\ pixel) \end{cases}$$
$$\boldsymbol{\hat{\delta}^V} = \begin{cases} \boldsymbol{G^V - R^V} & (at\ Red\ pixel) \\ \boldsymbol{G^V - R^V} & (at\ Blue\ pixel) \end{cases} \quad (10)$$

where the directional gradients are calculated as

$$D^H_{i,j} = \|\hat{\delta}^H_{i,j-1} - \hat{\delta}^H_{i,j+1}\|$$
$$D^V_{i,j} = \|\hat{\delta}^V_{i-1,j} - \hat{\delta}^H_{i+1,j}\| \quad (11)$$

The GBTF [11] estimates the missing pixel using directional color difference.

$$\begin{aligned} \hat{\delta}_{g,r}(i,j) =& \{\omega_N * \boldsymbol{f_{NE}} * \boldsymbol{\hat{\delta}^V_{g,r}(i-3:i,j)} + \\ & \omega_S * \boldsymbol{f_{SW}} * \boldsymbol{\hat{\delta}^V_{g,r}(i:i+3,j)} + \\ & \omega_E * \boldsymbol{\hat{\delta}^H_{g,r}(i,j-3:j)} * \boldsymbol{f^T_{NE}} + \\ & \omega_W * \boldsymbol{\hat{\delta}^V_{g,r}(i,j:j+3)} * \boldsymbol{f^T_{SW}}\}/\omega_T \\ & \omega_T = \omega_N + \omega_S + \omega_E + \omega_W \end{aligned} \quad (12)$$

The weight for each direction is calculated by adding color difference gradients in that direction over a local window. Therefore, this weighted average can interpolate the color difference of the target pixel from that of the same area in the image.

$$\omega_E = (\sum_{a=i-1}^{i+1} \sum_{a=j}^{j+2} D^H_{a,b})^2, \omega_W = (\sum_{a=i-1}^{i+1} \sum_{a=j-2}^{j} D^H_{a,b})^2$$
$$\omega_N = (\sum_{a=i-2}^{i} \sum_{a=j-1}^{j+1} D^V_{a,b})^2, \omega_S = (\sum_{a=i}^{i+2} \sum_{a=j-1}^{j+1} D^V_{a,b})^2 \quad (13)$$

where, $\boldsymbol{f}$ is a Gaussian weighted average filter. GBTF uses the simple average filter, but a Gaussian weighted average filter is far better .

$$\boldsymbol{f_{NE}} = [0.01, 0.08, 0.35, 0.56],$$
$$\boldsymbol{f_{SW}} = [0.56, 0.35, 0.08, 0.01], \quad (14)$$

Finally, the green pixel is calculated by adding the estimated color difference of the target pixel value that is originally obtained.

$$\hat{G}(i,j) = R(i,j) + \hat{\delta}_{g,r}(i,j),$$
$$\hat{G}(i,j) = B(i,j) + \hat{\delta}_{g,b}(i,j), \quad (15)$$

B. *Blue and Red interpolation*

We interpolate the red and blue pixel values after the green channel is interpolated. We utilize the adaptive guided upsampling which is shown in II-B using the green image as the guide. In this step, we decided to utilize a 5×5 window and Laplacian minimization in the guided upsampling.

IV. Experimental Results

We evaluated the proposed algorithm with the IMAX dataset and the Kodak dataset because they have been generally used for evaluating demosaicking performance. The IMAX dataset [5] is composed of 18 images and the Kodak dataset [13] is composed of 24 images. We downsampled the full-color test images to

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the Bayer pattern [1] images and utilized the demosaicking methods. We compared our proposed method with four state-of-the-art demosaicking methods, Gradient Based Threshold Free color filter array interpolation (GBTF) [11], Four-Direction Residual Interpolation for Demosaicking (FDRI) [12], Residual interpolation for color image demosaicking (RI) [6] and Beyond Color Difference: Residual Interpolation for Color Image Demosaicking (MLRI) [9].

The average PSNRs and CPSNRs of the Kodak dataset and the IMAX dataset are shown in table I. The average PSNRs and CPSNRs of the IMAX dataset shows that our proposed method is the best among the five methods. Though the average PSNRs and CPSNRs are lower than the GBTF [11], Our proposed method is superior to the other guided filter methods(FDRI [12],RI [6],MLRI [9]). However, the GBTF algorithm is efficient only for the Kodak dataset and our proposed algorithm is the best in the average PSNRs and CPSNRs of the IMAX and the Kodak datasets. The visual evaluation of the demosaicked image is shown in Fig.4 and Fig.5. The results demonstrate that our proposed algorithm reduces the color artifacts of both the IMAX image and kodak image. These visual comparisons prove that our demosaicking method outperforms from the visual point of view.

V. Conclusion

In conclusion, we proposed a new guided upsampling in order to improve demosaicking performance. We confirmed that optimizing the guided upsampling can restore more accurate G, R and B bands, compared with the existing methods except the learning and literation-based methods because of the high calculation cost. Experimental simulation results on the Kodak and IMAX datasets that are commonly used to test the demosaicking performance demonstrate that our proposed algorithm can generate superior quality of the demosaicked image in both objective and subjective evaluation.

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