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Edge-Strength Filter Based CFA Interpolation Using H-H Frequency Sub-band Channels

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Abstract:
To lower the cost and minimize the size, most digital cameras use a single sensor array to capture color images. The most commonly used Color Filter Array(CFA) is bayer pattern. In this pattern, at each pixel position only one color instead of three primary colors (Red,Green,Blue) is captured with CFA. The process by which full color image is reconstructed by interpolating the missing color samples is known as CFA Interpolation or demosaicking. The quality of reconstructed full color image is directly determined by the performance of the demosaicking algorithm. In this paper, we propose an algorithm to the demosaicking problem. The proposed demosaicking algorithm focuses on to estimate high-high(H-H) frequency components of the missing color channel in each color region and apply an edge strength filter which improves the initial green channel interpolation. Ourresultsshowsthattheproposeddemosaicking algorithm caneffectivelyinterpolatethetest imagesandthe original color can be faithfully reproduced with minimal amount of color artifacts even at edges. Comparisonswith other demosaickingapproaches based on preprocessing andtime complexitydemonstrate thesuperiorperformance ofthe proposed algorithm.
***Keywords*—**Bayer pattern, color filter array(CFA), Interpolation, demosaicking, edge-strength filter, edge directed interpolation.

I. INTRODUCTION

In quest of low cost, compact size, and long battery life, most digital cameras use a single sensor array to capture color images. At each pixel position only one instead of three primary colors (red, green, and blue) is captured with a color filter array (CFA). The most commonly used single sensor array is that of Bayer pattern [1] shown in Fig. 1. It consists of alternating red and green components at the odd rows and green and blue components at the even rows. This means that the camera must estimate the missing two color values at each pixel. This estimation process is known as CFA interpolation or demosaicking.

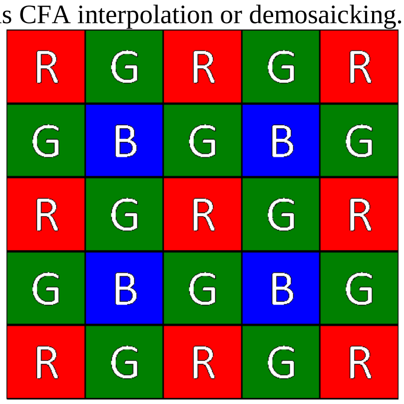


Fig.1. Bayer Pattern

The quality of reconstructed full color image is directly determined by the performance of the demosaicking algorithm.
If demosaicking is not performed appropriately, images suffer from highly-visible color artifacts. Obtaining better demosaicking performance is possible by exploiting the correlation between the color channels. Gunturk*et al.* have demonstrated that the high-frequency components of three color planes are highly correlated, with correlation values ranging from 0.98 to 1 [2]. Under this assumption, many of the existing demosaicking algorithms substitute the high-frequency components of the missing channel with those of the alternative pixel channel [2-8]. To better preserve high frequency information in demosaicking, the key is to exploit the strong correlations across color components.
As a result, Zhang proposed a hybrid approach which utilizes the strong correlation of the inter-channel high-frequency components, with the linear minimum mean-square estimation (LMMSE) and the support vector regression [4], while Chang exploited the effective use of spatial and spectral correlations (EUSSC) technique to improve the quality of the demosaicked image [5]. But this EUSSC technique produces color artifacts in the areas of weak spectral

correlations. An adaptive filtering method for better preservation of high-frequency information was introduced by Lian*et al.* [7]. It suggests that, filtering the CFA image as a whole instead of individual color channels should preserve high frequency information better. Since this method is iterative one, it increases the computational complexity.Gunturk*et al.* have reported that the high-frequency contents between different color planes are strongly correlated, and demonstrated this property by calculating the correlation values between the detail (high-frequency) wavelet coefficients [2]. Based on the strong correlation, they proposed to reconstruct the aliased detail wavelet coefficients in the red and blue planes from those of the green plane, which are more densely sampled. Their method achieves good performance. This method implies that in demosaicking, we could reconstruct a full-resolution image plane containing the high-frequency information, and then use it to estimate the missing color values.

In [8],Glotzbach*et al.* proposed a method for improving red and blue channel interpolation by adding high frequency components extracted from green channel to red and blue channels. Another approach that exploits inter-channel correlation is edge-directed interpolation[6]. This approach uses adaptive interpolation to prevent interpolating across edges. Several methods proposed performing interpolation in both horizontal and vertical directions and making a posteriori decision based on some criteria [9-10].

In this paper, we present a very effective means of using inter-channel correlation in demosaicking. First, the**H**igh-**H**igh **F**requency **S**ub-**B**and (HHFSB) for the missing color channel is analyzed. After that, we expand the reconstructed HHFSB with an edge strength filter. This stage also includes the cost associated with horizontal and vertical direction that considers edge strengths in order to preserve edge details and improve the initial green channel interpolation. After reconstructing the green plane, the red and blue planes are interpolated.

The paper is organized as follows. Section II presents the key concept of our approach. From the foundation, our entire proposed algorithm is described in Section III. Experimental results and performance comparisons with other methods are given in Section IV. Section V concludes the study.

II. KEY CONCEPTS

Our idea starts from the widely accepted assumption that the high-frequency components of three color planes are highly correlated. Furthermore, we use the assumption that their magnitudes are almost the same, meaning that the alternative high frequency component of red (*R*) or blue (*B*) can be used instead of the high frequency component of green (*G*). In this section, we identify that a edge directed interpolation method can also be driven on these assumptions. We expand this method with an Edge-Strength filter, thus finally form a basis ofour approach to reconstruct missing color channels.

A. High-Frequency Components

An image can be treated as the combination of its low and high frequency components. That is,

$$I = f_L(I) + f_H(I) \quad (1)$$

where$I$ indicates an image component that belongs to any of *RGB* channels, and $f_L(I)$ and $f_H(I)$ stand for low and high frequency components respectively. This image decomposition concept has been applied to various applications such as image sharpening, blurring, filtering and so on, and has been a good basis for various CFA interpolation methods.

In some cases, when we interpolate G channel of a CFA image, the high frequency term of the channel is often substituted with that of an alternative color channel,

$$G \cong f_L(G) + f_H(A) \quad (2)$$

where$f_L(G)$ is the low frequency component of G channel, and $f_H(A)$ represents the alternative high frequency component of R or B channel. The method of Hamilton *et al.* [9] can be interpreted to utilize this, because $f_H(A)$ was used instead of the second derivative of G. This means that the similarity of inter-channel components gets higher as their frequency goes higher. This leads us to the assumption,

$$f_H(G) \cong f_H(A) \quad (3)$$

where the high frequency component of R or B channel can be used instead of that of G channel.

B. Edge-Strength Filter

Edge detection filters can tell whether an edge structure is present at a given pixel or not. However, they do not provide any information aboutthe sharpness of luminance transition at thatparticular pixel. An edge strength filter that provides local, orientation-free luminance transition information [11]. The filter has a 3 by 3 support size. Given a grayscale input image (see Fig. 2.), it could be formulated as (4),

$$S_{P_5} = \frac{|P_1 - P_9|}{2} + \frac{|P_3 - P_7|}{2} + |P_2 - P_8| + |P_4 - P_6| \quad (4)$$

where S_{P5} stands for the edge strength at pixel location P_5. By applying the filter to all available pixels, we get the edge strength map of the input image. Note that, although the filter result for a single pixel does not provide any edge direction information, the relationship between neighboring pixel results yields the edge orientation in that neighborhood.

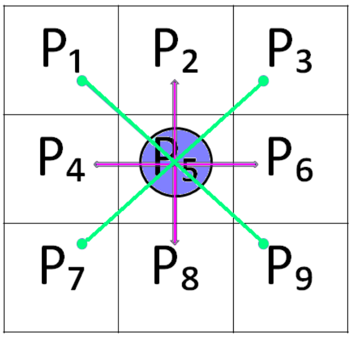


Fig.2. Edge strength at pixel p_5

This filter is very useful for finding edges in a grayscale image. However, a mosaicked image only has one of the three color channels available for every pixel location and it certainly does not have complete luminance information at any pixel. That is why, the edge strength filter can only be applied to a mosaicked image by making an approximation. Instead of trying to estimate luminance information and taking estimated luminance differences of neighboring pixel pairs, we take the difference in terms of the available color channel for each pixel pair.

The edge strength map obtained from the mosaicked input image will help us both in initial green channel interpolation stage and in subsequent green channel update.

III. PROPOSED ALGORITHM

The demosaicking algorithm that we propose consists of four main steps, depicted in Fig. 3: 1) HHFSB extraction; 2) Green

Fig.3. Block diagram of the proposed algorithm

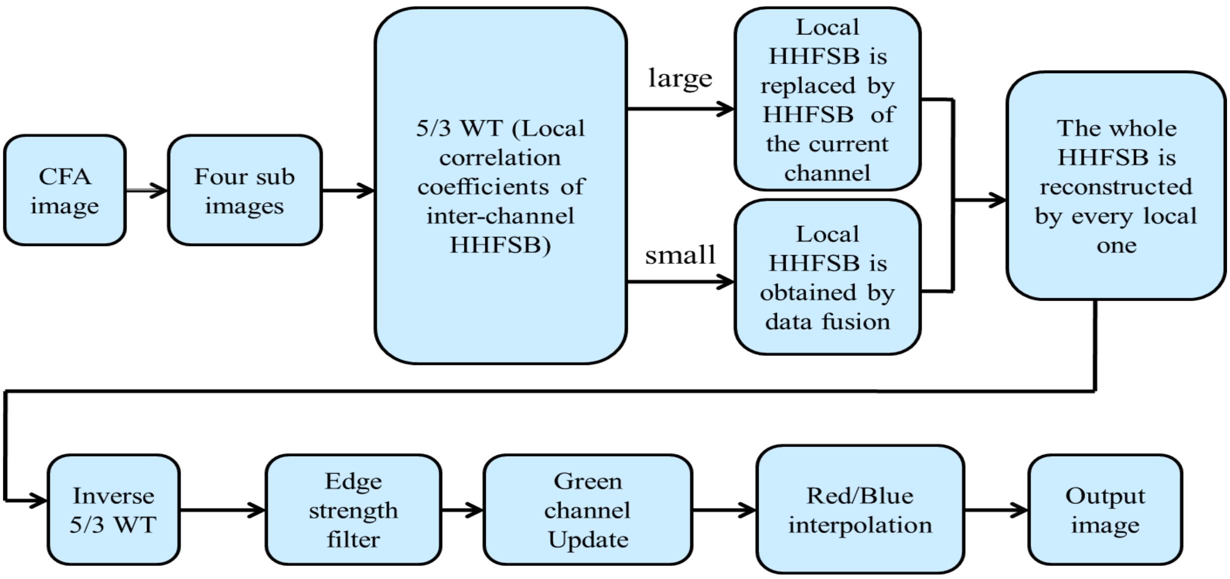
channel interpolation; 3) Green Channel Update; and 4) Red/Blue Channel Interpolation.

1) *HHFSB Extraction*

The input to our algorithm is a CFA image. Firstly, the CFA image is extracted intofour sub-images ie) Red (R), Blue (B) and Green channels are extracted separately. Since the density of green channel is twice than the red and blue channels, the green channel alone is extracted into two sub-images namely G1 and G2.

Secondly, the sub-imagesare decomposed by 5/3 wavelet transform (WT) and the localcorrelation coefficients of the inter-channel HHFSB arecalculated. The correlation coefficients of local HHFSB in the4×4 matrix between sub-image B and G1 and sub-image Band G2, named as $C_{bg1(m,n)}$ and $C_{bg2(m,n)}$ are calculated asfollows [12]:

$$C_{bg1(m,n)} = \frac{\sum_{i=m}^{m+3}\sum_{j=n}^{n+3}(WB_{ij}-\overline{WB_{ij}})(WG1_{ij}-\overline{WG1_{ij}})}{\sqrt{\sum_{i=m}^{m+3}\sum_{j=n}^{n+3}(WB_{ij}-\overline{WB_{ij}})^2}\sqrt{\sum_{i=m}^{m+3}\sum_{j=n}^{n+3}(WG1_{ij}-\overline{WG1_{ij}})^2}} \quad (5)$$



$$C_{bg2(m,n)}=\frac{\sum_{i=m}^{m+3}\sum_{j=n}^{n+3}(WB_{ij}-\overline{WB_{ij}})\left(WG2_{ij}-\overline{WG2_{ij}}\right)}{\sqrt{\sum_{i=m}^{m+3}\sum_{j=n}^{n+3}(WB_{ij}-\overline{WB_{ij}})^2}\sqrt{\sum_{i=m}^{m+3}\sum_{j=n}^{n+3}\left(WG2_{ij}-\overline{WG2_{ij}}\right)^2}} \quad (6)$$

where WB_{ij}, $WG1_{ij}$ and $WG2_{ij}$ are the wavelet coefficients oflocal HHFSB in 4×4 matrix, $\overline{WB_{ij}}$, $\overline{WG1_{ij}}$ and $\overline{WG2_{ij}}$ are themean values of the local HHFSB wavelet coefficients in 4×4matrix. m and n are the initial horizontal and verticalcoordinates of the wavelet coefficients in 4×4 matrix.

The accuracy (δ) of the proposed methodis set to 0.8inthis paper.There are two schemes to estimate the HHFSB of themissing green channel:

(a) When both of the local correlation coefficients aremore than δ, the correlation of the interchannelHHFSB in this local region is strong. At this moment, the HHFSB of the missing color channelin this local region will be replaced by that of the currentcolor channel.

(b) When at least one of the local correlation coefficients is less than δ, the correlation of the interchannel HHFSB in this local region is weak. At this moment, fuse theHHFSB of the adjacent pixels with the same color channelas the missing one.

Two schemes are illustrated asfollows:

$$\begin{cases} C\hat{D}\_g(m+i,n+j)=CD\_b(m+i,n+j) & if\ (C_{bg1(m,n)},C_{bg2(m,n)}\geq\delta) \\ C\hat{D}\_g(m+i,n+j)=w_1CD\_g1(m+i,n+j)+w_2CD\_g2(m+i,n+j) & else \end{cases} \quad (7)$$

where $C\hat{D}\_g$ is the estimate value of the HHFSB waveletcoefficient of the missing green value at blue pixel.CD_b,CD_g_1 and CD_g2 are the HHFSB wavelet coefficients ofthe sub-images B, G1 and G2. $w_1$and w_2 are the weightingfactors in the 4×4 matrix, $w_1+w_2 = 1$. i and j are thehorizontal and vertical coordinate in 4×4 matrix.

Thus the whole HHFSB of the missing green channelis obtained by scheme (a) or (b) in every local region. The missing green values at red pixels can be reconstructed with the similar method. Finally, the wholereconstructed HHFSB of the missing color channel is used tosynthesize the full color image.

2) Green Channel Interpolation

After reconstructing whole HHFSB, inverse 5/3WT is applied and then an edge-strength filter is applied to find the edge strength at each pixel. Green channel interpolation can be done by making a hard decision based on the edge strength filterdescribed in Section II. For this purpose, every green pixel to be interpolatedis marked either horizontalor vertical by comparing the edge strength differences along each directionon a local window. For a window size of 5×5, horizontal andvertical difference costs can be calculated as (8) and (9),

$$H_{i,j}=\sum_{m=-2}^{2}\left(\sum_{n=-2}^{1}(S_{i+m,j+n}-S_{i+m,j+n+1}\right) \quad (8)$$

$$V_{i,j}=\sum_{m=-2}^{1}\left(\sum_{n=-2}^{2}(S_{i+m,j+n}-S_{i+m+1,j+n}\right) \quad (9)$$

where $S_{i,j}$ is the edge strength filter output at the pixel location (i,j), and $H_{i,j}$ and $V_{i,j}$ represent the total horizontal and vertical costs respectively.

The target pixel will be labeled horizontal if horizontal cost is lessthan vertical and vice versa. The rationale behind this decision schemeis that if there happens to be a horizontal edge in a given neighborhood,then the edge strength differences between vertical neighbors will vary more than those of horizontal neighbors. After all the pixels are labeled, the robustness of the direction decision can be improved by relabelingthem based on the directions of their neighbors. Based on the final direction label, green channel is interpolated asfollows:

$$\tilde{G}_{i,j}=\begin{cases} B_{i,j}+\frac{\tilde{G}^H_{i,j}-B_{i,j}}{2}+\frac{G_{i,j-1}-\tilde{B}^H_{i,j-1}}{4}+\frac{G_{i,j+1}-\tilde{B}^H_{i,j+1}}{4}, & if horizontal \\ B_{i,j}+\frac{\tilde{G}^V_{i,j}-B_{i,j}}{2}+\frac{G_{i-1,j}-\tilde{B}^V_{i-1,j}}{4}+\frac{G_{i+1,j}-\tilde{B}^V_{i+1,j}}{4}, & if vertical \end{cases} \quad (10)$$

where directional estimations are calculated as(11),(12),(13) and (14):

$$\tilde{G}^H_{i,j}=\frac{G_{i,j-1}+G_{i,j+1}}{2}+\frac{2*B_{i,j}-B_{i,j-2}-B_{i,j+2}}{4} \quad (11)$$

$$\tilde{G}^V_{i,j}=\frac{G_{i-1,j}+G_{i+1,j}}{2}+\frac{2*B_{i,j}-B_{i-2,j}-B_{i+2,j}}{4} \quad (12)$$

$$\tilde{B}^H_{i,j}=\frac{B_{i,j-1}+B_{i,j+1}}{2}+\frac{2*G_{i,j}-G_{i,j-2}-G_{i,j+2}}{4} \quad (13)$$

$$\tilde{B}^V_{i,j}=\frac{B_{i-1,j}+B_{i+1,j}}{2}+\frac{2*G_{i,j}-G_{i-2,j}-G_{i+2,j}}{4} \quad (14)$$

Green channel estimation for red pixel locations is performed simplyby replacing B's with R's in the equations above.

3) Green Channel Update

The next step is updating the green channel. We make use of the constant color difference assumption combined with edge strength filter to improve the initial green channel interpolation
while avoiding averaging across edge structures. For everygreen pixel to be updated, the closest four neighbors with availablecolor difference estimates are considered.We expect the edge strengthdifference between two pixels to be large across edges. That is why theweight for each neighbor is inversely correlated with the total absoluteedge strength difference in its direction. In other words, a neighbor willcontribute less to the update result if there happens to be a strong edgebetween the target pixel and itself. Assuming we are updating the greenchannel value at a blue pixel can be done as follows:

$$D_1 = |S_{i,j} - S_{i-1,j}| + |S_{i-1,j} - S_{i-2,j}| + |S_{i-2,j} - S_{i-3,j}| + C_1$$
$$D_2 = |S_{i,j} - S_{i,j-1}| + |S_{i,j-1} - S_{i,j-2}| + |S_{i,j-2} - S_{i,j-3}| + C_1$$
$$D_3 = |S_{i,j} - S_{i,j+1}| + |S_{i,j+1} - S_{i,j+2}| + |S_{i,j+2} - S_{i,j+3}| + C_1$$
$$D_4 = |S_{i,j} - S_{i+1,j}| + |S_{i+1,j} - S_{i+2,j}| + |S_{i+2,j} - S_{i+3,j}| + C_1 \quad (15)$$

$$M_1 = D_2 * D_3 * D_4,\ M_2 = D_1 * D_3 * D_4,$$
$$M_3 = D_1 * D_2 * D_4,\ M_4 = D_1 * D_2 * D_3 \quad (16)$$

$$\hat{G}_{i,j} = B_{i,j} + W * \left(\tilde{G}_{i,j} - B_{i,j}\right) + (1-W) * \begin{bmatrix} \frac{M_1}{M_{Total}}\left(\tilde{G}_{i-2,j} - B_{i-2,j}\right) + \frac{M_2}{M_{Total}}\left(\tilde{G}_{i,j-2} - B_{i,j-2}\right) + \\ \frac{M_3}{M_{Total}}\left(\tilde{G}_{i,j+2} - B_{i,j+2}\right) + \frac{M_4}{M_{Total}}\left(\tilde{G}_{i+2,j} - B_{i+2,j}\right) \end{bmatrix} \quad (17)$$

$$M_{Total} = M_1 + M_2 + M_3 + M_4 \quad (18)$$

Again, green channel values at red pixel locations are updated inthe same way by replacing B’s with R’s in the equations above. $\hat{G}_{i,j}$ stands for updated green channel result while $\tilde{G}_{i,j}$ is the initial greenchannel interpolation. *C_1*is a nonzero constant to avoid zero denominator.*W_1*is the weight for the initial color difference estimation and*W_2* is the neighbors’ contribution to the green channel update. Experiments on test images suggest that one or two green channel updates are adequate.

4) Red/Blue Channel Interpolation

Once the green channel interpolation is finalized, we fill in red and blue channels using constant color difference assumption. For red channel interpolation at blue pixels and blue channel interpolation at red pixels, diagonal neighbors are used adaptively based on green channel gradients in both directions as (19):

$$M_1 = |\hat{G}_{i-2,j-2} - \hat{G}_{i,j}| + |\hat{G}_{i-1,j-1} - \hat{G}_{i+1,j+1}| + |\hat{G}_{i,j} - \hat{G}_{i+2,j+2}|$$
$$M_2 = |\hat{G}_{i-2,j+2} - \hat{G}_{i,j}| + |\hat{G}_{i-1,j+1} - \hat{G}_{i+1,j-1}| + |\hat{G}_{i,j} - \hat{G}_{i+2,j-2}| \quad (19)$$

If coordinate *(i, j)* is a red pixel location, blue channel estimation iscalculated as follows:

$$\hat{B}_{i,j} = \hat{G}_{i,j} - \frac{M_2 * \left(\hat{G}_{i-1,j-1} - B_{i-1,j-1} + \hat{G}_{i+1,j+1} - B_{i+1,j+1}\right)}{2*(M_1 + M_2)} - \frac{M_1 * \left(\hat{G}_{i-1,j+1} - B_{i-1,j+1} + \hat{G}_{i+1,j-1} - B_{i+1,j-1}\right)}{2*(M_1 + M_2)} \quad (20)$$

The equations are similar for red channel estimation at a blue pixellocation.

For red and blue channel estimation at green pixels, we employ bilinearinterpolation over color differences since considered adaptive approaches do not provide any performance gain. Here, only the closest two neighbors for which the original pixel value available are used as (21) and (22):

$$\hat{B}_{2i,2j} = G_{2i,2j} - \frac{\left(\hat{G}_{2i-1,2j} - B_{2i-1,2j}\right) + \left(\hat{G}_{2i+1,2j} - B_{2i+1,2j}\right)}{2} \quad (21)$$

$$\hat{B}_{2i+1,2j+1} = G_{2i+1,2j+1} - \frac{\left(\hat{G}_{2i+1,2j} - B_{2i+1,2j}\right) + \left(\hat{G}_{2i+1,2j+2} - B_{2i+1,2j+2}\right)}{2} \quad (22)$$

By the end of this step, we filled in all the missing color channelvalues in the input image.

IV. EXPERIMANTAL RESULT

To evaluate the performance of the proposed method, we start by selecting 15 test images from Kodak image suite shown in Fig. 4. These include the commonly used benchmark images.

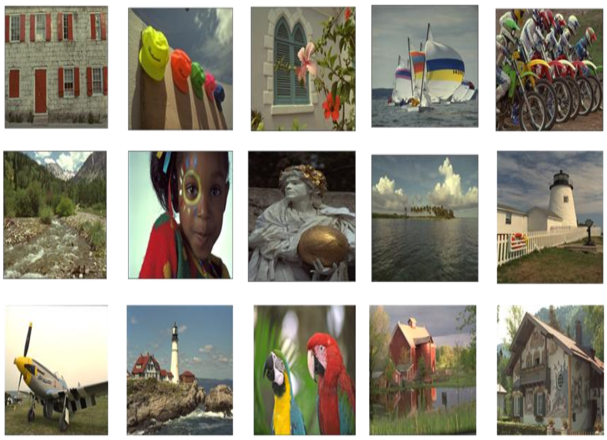


Fig.4. The test images of Kodak dataset

For all the test images, first the CFA images are generated by sampling the original images using the Bayer pattern. The proposed algorithm is implemented as following the steps explained in Section III.

Results of the proposed algorithm are compared with the popular method of Hamilton and Adams (HA) [9], Enhanced Effective Color Interpolation (EECI) [5], Alternating Projections(AP) [2], Adaptive Filtering method (AF) [7] and Edge Strength Filter(ESF) [11]. The peak signal-to-noise ratio (PSNR) values of these methods are summarized in Table 1.The PSNR value is used to appraise these methods and is defined as (23),

$$PSNR = 10\log_{10} \frac{255^2 \ M \ N}{\sum_{i=1}^{M} \sum_{j=1}^{N} (f(i,j) - f'(i,j))^2} \quad (23)$$

Where $f(i,j)$ and $f'(i,j)$ denote the pixel values of original image and restored image respectively, M and N are the size of the testing images. The boldface numbers indicates the highest values obtained for each image. From this, we can see that the proposed algorithm got higher PSNR values than other demosaickingmethods. Hence the performance of the proposed method is improved than the existing demosaicking algorithms. The proposed method yields good results with reduced computational cost, thus it is possible to implement in simple low-cost cameras.

TABLE I

Comparison of PSNR values for different demosaicking methods

Image No	HA	EECI	AP	AF	ESF	proposed
1	34.69	40.65	41.16	39.71	43.55	**43.90**
2	40.86	43.99	39.94	44.07	42.65	**44.87**
3	42.18	45.63	42.75	45.47	43.17	**47.77**
4	40.63	43.46	36.40	43.72	38.51	**46.09**
5	35.96	40.96	43.16	40.74	**44.28**	43.13
6	36.08	41.18	40.36	40.52	41.82	**45.38**
7	42.29	45.46	42.87	45.68	45.75	**47.02**
8	33.46	38.65	**41.92**	37.92	40.65	41.72
9	41.47	45.49	42.05	45.16	42.84	**48.14**
10	41.36	45.59	40.16	45.54	41.75	**47.46**
11	37.17	42.18	39.15	41.62	39.89	**45.17**
12	42.31	45.76	45.70	45.63	43.50	**48.47**
13	30.65	36.86	36.68	35.72	37.54	**40.31**
14	37.27	40.56	38.99	40.45	**41.32**	41.25
15	39.44	42.84	41.56	43.05	42.21	**44.55**

V. CONCLUSION

We presented a demosaicking algorithm for the problem of interpolating H-H frequency sub-band channels. A simple Edge-strength filterisatechniqueapplied to H-H frequency components to interpolate missing color channels. We utilized this simple edge strength filterboth to determine the initial green channel interpolation direction andto avoid applying constant color difference rule across edge structures.Inthispaper,we proposedanew method to interpolate the H-H frequency sub-band channels to get better reconstruction results. The proposed method improves the demosaickingperformance by estimating H-H frequency components using 5/3 wavelet transform and applying edge-strength filter to the interpolation problem. The effective use of edge-strength filter is to improve initial green channel interpolation by reducing color artifacts. And it also preserves the edges during interpolation. Preliminaryresults revealedthattheproposeddemosaicking algorithm caneffectivelyinterpolatethetest imagesandthe original color can be faithfully reproduced with minimal amount of color artifacts even at edges.

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