CFA DEMOSAICKING BY ADAPTIVE ORDER OF APPROXIMATION

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Abstract: Colour filter array (CFA) demosaicking refers to determining the missing colour values at each pixel when a single-sensor digital camera is used for colour image capture. It has recently been shown that missing colour values can be interpolated or extrapolated using Taylor series. The accuracy of approximation depends on the number of high order derivative terms included in the Taylor series. For a smooth region of an image, the higher the order, the higher the accuracy in the approximation of the missing colour values. However, the estimation of high order derivative terms requires pixel values from a wider area of neighbourhood. When an image contains features closely spaced together, extrapolation using pixels from a smaller region of neighbourhood is preferred and a low order of approximation should be applied. In order to achieve more accurate results, we propose an algorithm using an adaptive order of approximation depending on the colour smoothness of the image. It has been shown that our algorithm outperforms other techniques for various images, and in particular for images with the above mentioned characteristics.

1 INTRODUCTION

Colour filter array (CFA) demosaicking is the determination of missing colour values at each pixel when using a single-sensor digital camera for colour image capture. In this paper, we introduce an algorithm using an adaptive order of approximation to recover missing colour information which depends on the colour smoothness of an image. Our method is divided into two stages. In the first stage, we use the local colour smoothness of the image to adaptively determine the appropriate order of extrapolation for the green plane. This will be applied independently to produce one estimate for each of the four possible directions, namely up, down, left and right.

The second stage determines the best estimate out of the possible four directional estimates, using a classifier instead of a linear combiner. Other demosaicking methods (Kimmel 1999, Lu&Tan 2003) determine the missing colour values by combining weighted estimates from corresponding directions. Inaccurate estimation of weightings will produce artifacts which manifest themselves in the demosaicked output.

The remainder of the paper is organized as follows. Section 2 details the extrapolation method of various orders. Section 3 presents the experimental results, and compares this method with other existing methods, with the conclusion given in Section 4.

2 ADAPTIVE ORDER OF APPROXIMATION

The most common colour filter array used is the Bayer CFA (Bayer 1976). Figure 1 shows an 8 x 8 window of a Bayer array neighbourhood, where the index (i,j) denotes the row and column of each colour pixel. For the Bayer pattern, the green colour is sampled at twice the rate of the red and blue values. This is due to the peak sensitivity of the human visual system which lies in the green spectrum (Bayer 1976).

To estimate the green value at position x (G_x) at which only the blue value (B_x) is known, consider the one-dimensional case with an edge boundary on the left-hand side of B_x, as shown in Figure 2.

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Figure 1: 8x8 Bayer pattern.

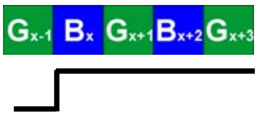

Figure 2: 1D Bayer Pattern and Edge Boundary on the left-hand-side of B_X.

(1), (2) and (3) are the zero, first and second order extrapolation equations for the determination of the missing green colour $\hat{G}_x$ respectively (Li&Randhawa 2005a). From these equations the higher the order of approximation, the more higher order correction terms are included to improve the accuracy. However this implies that more samples from an extended area of neighbourhood are required for the approximation.

$$\text{Zero Order: } \hat{G}_x = G_{x+1} \tag{1}$$

$$\text{First Order: } \hat{G}_x = G_{x+1} + \tfrac{1}{2}(B_x - B_{x+2}) \tag{2}$$

Second Order:

$$\hat{G}_x = G_{x+1} + \tfrac{3}{4}(B_x - B_{x+2}) - \tfrac{1}{4}(G_{x+1} - G_{x+3}) \tag{3}$$

Zero order approximation uses the nearest neighbour to estimate the missing colour value in the direction of the extrapolation. It gives satisfactory results for regions containing features closely spaced together. In this case, the zero order avoids using pixels from other nearby non-related features in the estimation.

For regions with little colour variation, the general assumptions for demosaicking will hold (Lu&Tan 2003), and the second order will give the best accuracy. For regions with moderate colour variation, the first order will be applied.

The second order will provide adequate accuracies for most applications, and third or higher orders of approximation are not required (Li&Randhawa 2005a).

For the red/blue missing colour values, it has been shown that first order extrapolation will give satisfactory results for most images ((Li&Randhawa 2005b).

2.1 Ideal Selector

To confirm that different orders of approximation will perform better in different regions of an image, we apply an ideal selector to determine which order is the best choice for each missing pixel in the green plane.

To illustrate the above mentioned concept, we use the pixels in the original image to select one of the twelve estimates (four directional estimates from each order) based on the minimum mean square error criterion. Figures 3 and 4 show the original and the ideal selector output of the popular Lighthouse image. These two images are visually indistinguishable from each other (MSE = 0.0122) and this indicates clearly that the selected output is a very good approximation of the original. This confirms the presence of a highly accurate estimate within the twelve extrapolated choices. Table 1 gives the proportion for each order as the best choice for Figure 3. (The undecided proportion in Table 1 represents those pixels that have identical values for different orders and hence no unique order can be decided.)

Table 1: Best choices for each order.

Order	Best Choice
Zero	30 %
First	24 %
Second	30 %
Undecided	16 %

In general, different images will have different proportions for different orders but will normally have some proportion for each order. Hence we propose an adaptive algorithm to select one of the three orders according to the colour smoothness of the image to achieve better results.

Figure 3: Original Lighthouse image.

Figure 4: Ideal selector output.

2.2 Adaptive Algorithm

An indicator to determine the colour smoothness is proposed as follows. Based on the idea of the hue assumption (Cok 1987), we define that the colour is smooth when (4) is satisfied when estimating a missing green value at a blue pixel location. A similar equation applies for the estimation of a missing green value at a red pixel location. In this case, when the difference between the variations in blue and green is small, the hue assumption is valid, and hence we can apply the highest (second) order of extrapolation to obtain the best results. Experimentally, a normalised value of 0.7 for ε will give satisfactory results for most images.

$$\left| \left| B_X - B_{X+2} \right| - \left| G_{X+1} - G_{X+3} \right| \right| \leq \varepsilon \quad (4)$$

Otherwise, if the variation in blue (or red) is greater than the variation in green (5), this may indicate a colour edge in blue (or red) and so the hue assumption does not apply. Hence the zero order is preferred. In this case the application of the invalid hue assumption in the estimation of the missing colour pixel can be avoided.

$$\left| B_X - B_{X+2} \right| > \left| G_{X+1} - G_{X+3} \right| \quad (5)$$

However, if the variation in green is greater than the variation in blue, the first order is chosen because this indicates that there is no colour edge in blue, and so half of the small variation in blue will be included to improve the accuracy in the estimation of the green value as shown in (2).

Similarly, one estimate for each of the four directions, namely up, down, left and right, can be found by (1) to (5). The next step is to use a classifier to select the best choice out of the four candidates. Since a linear combiner, as used in other methods (Kimmel 1999, Lu&Tan 2003) will blur an edge, a median-based classifier (Li&Randhawa 2005a) which will preserve sharp edges is used instead.

In the classifier stage, an orientation matrix for every pixel is produced using the CFA image input. This is used to indicate the possible orientation of an edge for that pixel. The underlying assumption made is that the neighbourhood orientation must be aligned in a direction along an edge (Li&Randhawa 2005b).

The orientation matrix (Li&Randhawa 2005a) is used to reject one sample before we apply median filtering. This is because an odd window width for the median filtering is preferred in order to avoid blurring an edge. The classifier algorithm is depicted as a flowchart in Figure 5. If it is a '1' in the orientation matrix, a possible vertical edge exists and hence one of the two estimates in the horizontal direction will be rejected. Similarly for a '0' in the orientation matrix, we reject an estimate in the vertical direction. The one out of the two to be rejected has the greatest difference in magnitude from the median of the four extrapolated estimates.

3 RESULTS

To evaluate the performance of our method against other demosaicking methods, the picket-fence region of the Lighthouse image in Figure 3 was used. This area represents a challenge for many demosaicking methods due to the presence of many edges close together. The image quality performance measures, using normalized color difference (NCD) (Plataniotis 2000) and mean squared difference (MSE), of the various demosaicking methods: Freeman (1988), Kimmel (1999), Hamilton (1997), Plataniotis (2004), Lu&Tan (2003), and Gunturk (2002), are tabulated as shown in Table 2. Our proposed method, with $\varepsilon = 0.7$, has the smallest error value among all the methods. Figures 6 to 14 show the sample demosaicked results from our proposed method and other methods under comparison. This supports our quantitative measures and illustrates that our method is also visually superior to other demosaicking methods as it has the least false colours in the high-frequency picket-fence region.

Table 2: Image Quality Performance Measure.

Method	NCD	MSE
Bilinear	0.1036	24.65
Freeman	0.0587	14.75
Kimmel	0.0687	17.35
Hamilton	0.0268	8.85
Plataniotis	0.0637	16.25
Lu&Tan	0.0163	5.05
Gunturk	0.0153	4.01
Our Proposed Method	0.0115	3.77

We also applied other types of images for the evaluation of our proposed method as shown in Figures 15 and 16. The results are tabulated in Table 3, and they confirm that our method is superior to other techniques.

4 CONCLUSION

An adaptive order of approximation algorithm has been proposed for colour filter array demosaicking. This method uses the colour smoothness of an image to determine a suitable order of approximation. It has been shown that our method outperforms other techniques visually and quantitatively. Research on its implementation for real-time processing is underway.

Table 3: NCD results for the demosaicking methods.

Method	NCD	
	Statue Image	Red Door Image
Bilinear	9.9222E-03	5.4689E-03
Freeman	5.9773E-03	4.1314E-03
Kimmel	7.2663E-03	5.8250E-03
Hamilton	6.9636E-03	4.0047E-03
Plataniotis	371.35E-03	530.98E-03
Lu&Tan	5.5855E-03	4.6519E-03
Gunturk	5.3888E-03	4.7444E-03
Our Proposed Method	5.1359E-03	3.9169E-03

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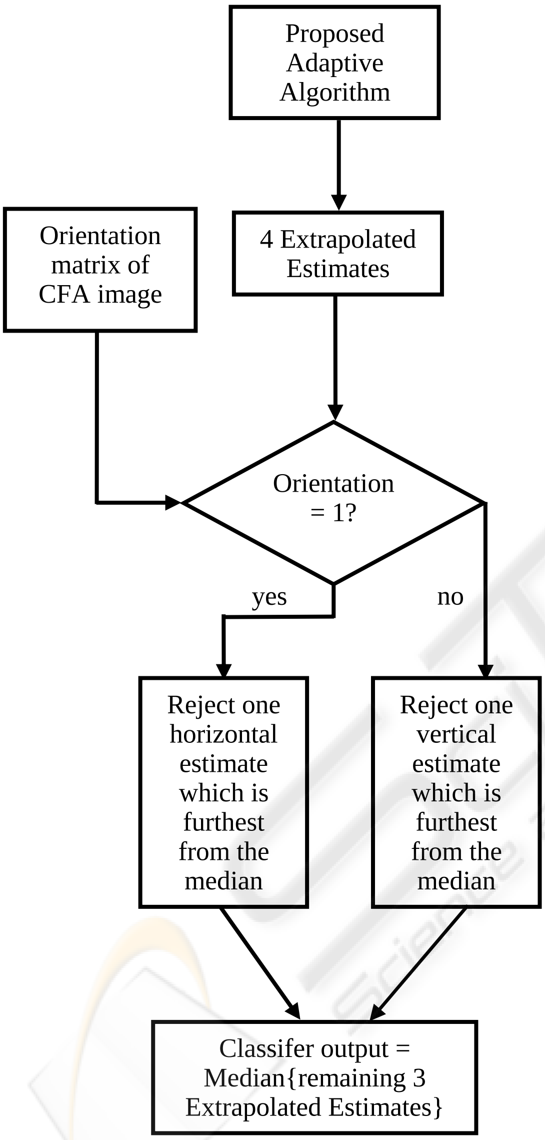

Figure 5: Flowchart of Classifier.

Figure 6: Original picket-fence from Lighthouse image.

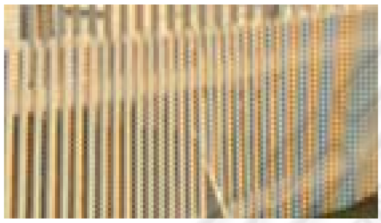

Figure 7: Bilinear Output.

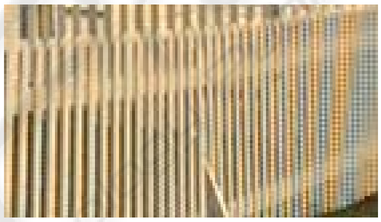

Figure 8: Freeman Output.

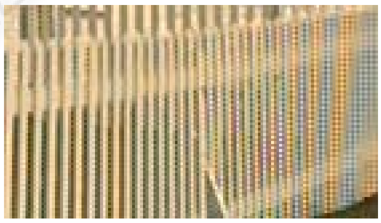

Figure 9: Kimmel Output.

Figure 10: Hamilton Output.

Figure 11: Plataniotis Output.

Figure 12: Lu&Tan output.

Figure 13: Gunturk output.

Figure 14: Our proposed method.

Figure 15: Statue Image.

Figure 16: Red Door Image.