Adaptive Colour Filter Array (CFA) Demosaicking with Mixed Order of Approximation

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Abstract

The estimation of missing pixel colour values when using a single-sensor digital camera for full colour image capture is known as colour filter array (CFA) demosaicking. It has recently been shown that missing colour values can be approximated using Taylor series with good accuracy. In order to prevent the appearance of colour artefacts around an edge boundary, it is desirable to avoid interpolation across an edge. By the application of an edge direction map, we can determine the preferred direction for interpolation, either vertically or horizontally for the green plane. In this paper, interpolation is carried out along a preferred direction and samples from both sides of the missing colour value are used. The order of approximation for the estimates on each side of the missing colour value is determined independently and adaptively depending on whether there is a nearby edge and its distance from the missing colour value. For example, if a colour edge is nearby, a lower order of approximation, which only uses samples close to the missing colour value, will be employed so as to avoid the inclusion of the colour edge. However, if a colour edge is further away on the other side of the missing colour value, a higher order of approximation for higher accuracy will be used instead. The missing colour value is then estimated by combining the estimates from both sides with their respective orders of approximation. This proposed method using mixed order of approximation has been shown to produce better performance than the method by selecting a single estimate as the output.

1. Introduction

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. The Bayer CFA is the most common colour filter array used [1]. Fig. 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. In this 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 [1].

In this paper, we use a mixed order of approximation determined adaptively to evaluate the missing colour values. This is based on the fact that the distance of a colour edge on one side could be different to the distance of the colour edge on the other side of the missing colour value.

This method is divided into two main stages. We first determine the preferred direction of interpolation, namely vertical or horizontal, by the use of an edge direction map based on the vertical and horizontal gradients. In this way, interpolation is carried out along edges rather than across them in order to avoid introducing colour artefacts. Once the preferred direction for interpolation has been ascertained, the second stage involves determining two estimates by employing samples from both sides of the missing colour value, along the preferred direction. The order of approximation is adaptively determined for the estimates on each side of the missing colour value depending on whether there is a nearby edge and its distance from the missing colour value. A lower order of approximation is used when a colour edge is nearby. It employs samples close to the missing colour sample in order to avoid the inclusion of colour edges. When a colour edge is further away, a higher order of approximation is employed. This uses more samples and can produce higher accuracy. Once the two estimates on each side of the missing colour have been determined, the missing colour is the average of these estimates with their respective orders of approximation.

The remainder of the paper is organized as follows. Section 2 details the adaptive order of demosaicking. Section 3 presents the experimental results, and compares the proposed method with other existing techniques, and the conclusion is given in Section 4.

Fig. 1: 8x8 Bayer pattern

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2. ADAPTIVE ORDER OF DEMOSAICKING

To estimate the green value at position x (G_x) at which only the blue value (B_x) is known, consider the one-dimensional horizontal case as shown in Fig. 2.

G_{x-3}	B_{x-2}	G_{x-1}	B_x	G_{x+1}	B_{x+2}	G_{x+3}

Fig. 2: 1D Bayer Pattern

The extrapolation equations for the determination of the missing green colour ($\hat{G}_x$) using samples from its right-hand side (RHS) for the zero, first and second order are given in (1a), (2a) and (3a) respectively [7]. Similarly, equations can be derived for the different orders of approximation in the vertical direction.

Zero Order:

RHS: $\hat{G}_x = G_{x+1}$ (1a)

LHS: $\hat{G}_x = G_{x-1}$ (1b)

First Order:

RHS: $\hat{G}_x = G_{x+1} + \frac{1}{2}(B_x - B_{x+2})$ (2a)

LHS: $\hat{G}_x = G_{x-1} + \frac{1}{2}(B_x - B_{x-2})$ (2b)

Second Order:

RHS: $\hat{G}_x = G_{x+1} + \frac{3}{4}(B_x - B_{x+2}) - \frac{1}{4}(G_{x+1} - G_{x+3})$ (3a)

LHS: $\hat{G}_x = G_{x-1} + \frac{3}{4}(B_x - B_{x-2}) - \frac{1}{4}(G_{x-1} - G_{x-3})$ (3b)

A. *Edge Orientation Map*

In this first stage of the proposed algorithm, an edge 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 [8]. This is done by calculating the vertical and horizontal gradients at every pixel.

For example at the blue pixel B_{45} in Fig. 1, we define the vertical gradient and horizontal gradient as:

$$V = |G_{35} - G_{55}|, \quad H = |G_{44} - G_{46}| \quad (4)$$

At the green pixel G_{46}, the vertical and horizontal gradients are defined as:

$$V = |R_{36} - R_{56}|, \quad H = |B_{45} - B_{47}| \quad (5)$$

A logical function is used to produce an orientation matrix for the whole colour filter array image:

$$f(V < H) = \begin{cases} 1, & \text{if } V < H \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

If it is a ‘1’ in the orientation matrix, a possible vertical edge exists and hence we only interpolate along this direction. Similarly for a ‘0’ in the orientation matrix, we interpolate along the horizontal direction.

B. *Adaptive Algorithm*

In order to determine the order of extrapolation, an indicator of colour edge occurrence is proposed as follows. Based on the idea of the hue assumption [2], we define that the colour is smooth, i.e. there are no nearby edges, when (7) is satisfied for the estimation of 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 higher accuracy. Experimentally, a normalised value of 0.7 for ε will give satisfactory results for most images.

$$\big|\,|B_x - B_{x+2}| - |G_{x+1} - G_{x+3}|\,\big| \le \varepsilon \quad (7)$$

Otherwise if the variation in blue is greater than the variation in green (8), this may indicate the presence of a colour edge in blue and thus violate the hue assumption. Hence the zeroth order is preferred.

$$|B_x - B_{x+2}| > |G_{x+1} - G_{x+3}| \quad (8)$$

However, if the variation in green is greater than the variation in blue, this may indicate the lack of a colour edge in blue and thus the first order is chosen. Hence only half of the small variation in blue will be included as shown in (2) to improve the accuracy in the estimation of the green value.

C. *Mixed Order of Approximation*

In the estimation process, we use samples from both sides the missing colour value, but split them into two different groups of samples. If the preferred direction is horizontal for example, one group includes LHS samples and the other RHS samples. The order of extrapolation is then adaptively determined for each group. The missing colour value is determined by averaging the left and right estimates according to the equations in Table 1. Fig. 3 gives the flowchart of our proposed algorithm.

Since the zeroth order is the lowest and the second order is the highest order of approximation, for our proposed method, all the possible combinations for the horizontal direction are shown in Table 1. Similarly equations for the vertical direction can be derived.

For example, if the order of approximation for the LHS group is first order and the RHS group is second order, the missing colour value is the average of the estimates of (2b) and (3a), and is given by (14) in Table 1.

The above adaptive order of extrapolation is applied for the determination of missing values in the green plane only. For the red and blue planes, a first order of approximation is sufficient to determine the missing colour values [7].

3. RESULTS

To assess the performance of our proposed algorithm, we compare our method with other demosaicking techniques. The picket-fence region of the Lighthouse image in Fig. 4 was used because it contains challenging features for many demosaicking methods due to the presence of many edges close together. The image quality performance measures, namely normalized color difference (NCD) [10] and mean squared difference (MSE), are tabulated in Table 2 for the various demosaicking methods: Freeman [3], Kimmel [6], Hamilton [5], Plataniotis [11], Lu&Tan [9], Gunturk [4] and Li&Randhawa [13]. Our proposed method ($\varepsilon = 0.7$), has the smallest error value among all the methods. Fig. 5(a)-(j) show the demosaicked results of our proposed method in comparison with other methods. This supports the results of our quantitative measures and confirms that our method is visually superior to other demosaicking methods as well, as it has the least false colours in the high-frequency picket-fence region.

TABLE 2: IMAGE QUALITY PERFORMANCE MEASURE

Demosaicking Method	NCD	MSE
Bilinear	0.1247	0.1810
Freeman	0.0751	0.1114
Kimmel	0.0836	0.1178
Hamilton	0.0371	0.0687
Plataniotis	0.0720	0.1131
Lu&Tan	0.0150	0.0338
Gunturk	0.0198	0.0325
Li&Randhawa	0.0091	0.0249
Our Proposed Method	0.0073	0.0232

Other types of images were applied for the assessment of our proposed method as shown in Fig. 6(a)-(e). The top-left corners of all the CFA test images start with a green pixel, as shown in Fig 1. The results are tabulated in Table 3, and they support the fact that our method is superior to other techniques. It is obvious that our proposed algorithm outperforms the method using a single estimate for the output [13] due to the fact that errors in the extrapolated output can now be averaged out. Since the averaging process is performed along the direction of an edge, it will not cause any blurring effects.

TABLE 1: MIXED ORDER OF APPROXIMATION

Order for Approximation on LHS of missing value	Equation to determine the missing green value ($\hat{G}_x$)	Order for Approximation on RHS of missing value
Zero	$\hat{G}_x = \frac{1}{2}(G_{x+1} + G_{x-1})$ (9)	Zero
Zero	$\hat{G}_x = \frac{1}{2}(G_{x+1} + G_{x-1}) + \frac{1}{4}(B_x - B_{x+2})$ (10)	First
Zero	$\hat{G}_x = \frac{1}{2}(G_{x+1} + G_{x-1}) + \frac{3}{8}(B_x - B_{x+2}) - \frac{1}{8}(G_{x+1} - G_{x+3})$ (11)	Second
First	$\hat{G}_x = \frac{1}{2}(G_{x+1} + G_{x-1}) + \frac{1}{4}(B_x - B_{x-2})$ (12)	Zero
First	$\hat{G}_x = \frac{1}{2}(G_{x+1} + G_{x-1}) + \frac{1}{4}(2B_x - B_{x+2} - B_{x-2})$ (13)	First
First	$\hat{G}_x = \frac{1}{2}(G_{x+1} + G_{x-1}) - \frac{1}{8}(B_x + 2B_{x-2} + 3B_{x+2}) - \frac{1}{8}(G_{x+1} - G_{x+3})$ (14)	Second
Second	$\hat{G}_x = \frac{1}{2}(G_{x+1} + G_{x-1}) + \frac{3}{8}(B_x - B_{x-2}) - \frac{1}{8}(G_{x-1} - G_{x-3})$ (15)	Zero
Second	$\hat{G}_x = \frac{1}{2}(G_{x+1} + G_{x-1}) - \frac{1}{8}(B_x + 2B_{x+2} + 3B_{x-2}) - \frac{1}{8}(G_{x-1} - G_{x-3})$ (16)	First
Second	$\hat{G}_x = \frac{1}{2}(G_{x+1} + G_{x-1}) + \frac{3}{8}(2B_x - B_{x+2} - B_{x-2}) + \frac{1}{8}(G_{x+3} - G_{x+1} - G_{x-1} + G_{x-3})$ (17)	Second

4. CONCLUSION

An adaptive CFA demosaicking algorithm has been proposed. The superior performance of our method is mainly due to the fact that the orders of approximation are determined adaptively to avoid the inclusion of near and far colour boundaries. This is because a lower order of approximation will only use samples in very close proximity to the missing colour value to avoid near colour boundaries, whereas a higher order approximation can utilise more samples further away from the missing colour value with better accuracy, without including the far colour boundaries. It has been shown that our method outperforms other techniques visually and quantitatively.

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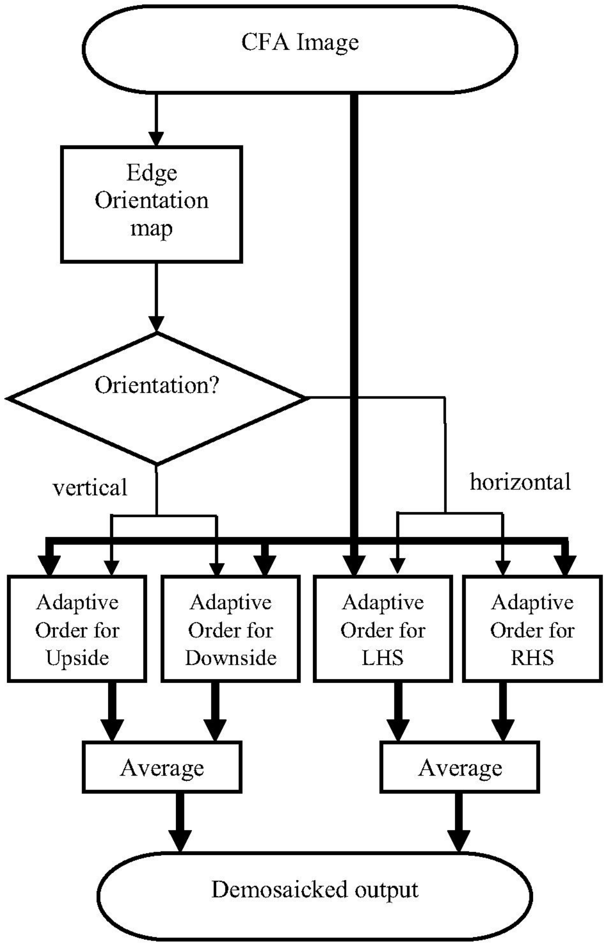
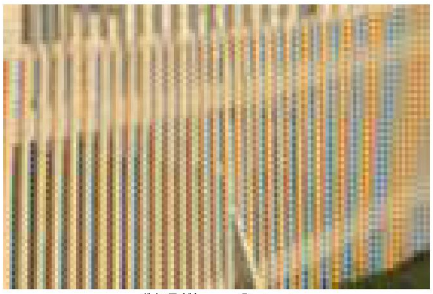


Fig. 3: Flowchart of Proposed Algorithm

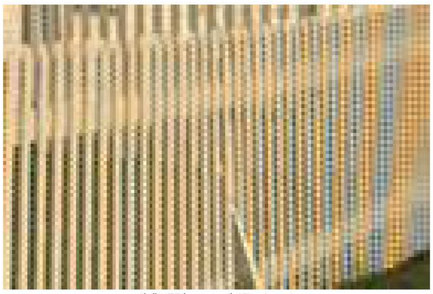
Fig. 4 Lighthouse Image

(a) Original Fence Region



(b) Bilinear Output

(c) Freeman Output



(d) Kimmel Output

(e) Hamilton Output

(f) Plataniotis Output

(g) Lu&Tan Output

(h) Gunturk Output

(i) Li&Randhawa Output

(j) Proposed Method Output

Fig. 5(a)-(j): Outputs from Various Demosaicking Methods

TABLE 3: NCD RESULTS FOR THE DEMOSAICKING METHODS

DEMOSAICKING METHODS	NCD VALUES				
	Fig. 5(a)	**Fig. 5(b)**	**Fig. 5(c)**	**Fig. 5(d)**	**Fig. 5(e)**
Bilinear	5.469E-03	7.691E-03	1.119E-02	9.922E-03	7.971E-03
Freeman	4.131E-03	3.781E-03	6.622E-03	5.977E-03	4.620E-03
Kimmel	5.825E-03	4.656E-03	9.212E-03	7.266E-03	5.754E-03
Hamilton	4.005E-03	4.769E-03	7.074E-03	6.964E-03	4.766E-03
Plataniotis	3.900E-03	6.000E-03	6.600E-03	8.600E-03	5.700E-03
Lu&Tan	4.123E-03	3.516E-03	5.540E-03	5.937E-03	4.186E-03
Gunturk	4.744E-03	3.566E-03	5.145E-03	5.389E-03	4.288E-03
Li&Randhawa	3.917E-03	3.796E-03	5.348E-03	5.136E-03	4.314E-03
Our Proposed Method	3.648E-03	3.333E-03	4.657E-03	4.680E-03	4.178E-03

(a)

(b)

(c)

(d)

(e)

Fig. 6(a)-(e): Test Images