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SHORT COMMUNICATION

Edge Strength based Fuzzification of Colour Demosaicking Algorithms

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ABSTRACT

In this paper we fuzzify the bilinear colour interpolation and the non-linear colour differential correlative interpolation techniques of colour demosaicking, using the edge strength map of the mosaic image. In doing so we ensure that the edges have less participation in the interpolation thereby minimizing the interpolation error. The result is faster and more accurate colour demosaicking algorithms with application to high resolution images. The overall improvement is quite significant when it comes to colour interpolation of high definition/high resolution images containing a lot of detail or edges as proved by the extensive experimental results on state-of-the-art databases and state-of-the-art comparison.

Keywords: Colour demosaicking, colour filter array interpolation, edge strength, fuzzy membership

1. INTRODUCTION

Digital Cameras containing single chip sensors are increasingly becoming popular due to their savings in cost and size. In a single chip camera sensor, at each pixel location, only one of the R, G, B channels are captured in the layout of the Bayer pattern[3] as shown in Fig. 1. The resulting image is called the mosaic image. Colour filter array interpolation (CFA) or demosaicking techniques[1,2] are used to generate the missing colour values using the existing colour values in the mosaic image. Since green colour samples show least aliasing, the green channel is interpolated first followed by the red and the blue channels[1,2]. Edge directed green channel interpolation was investigated before using both luminance and chrominance gradients[4,5]. Chrominance gradients were also used for initial green channel interpolation[7]. The edge strength filter output has been used to improve the green channel interpolation in an iterative manner leading to computational overhead[2]. It is established that high frequency details from the mosaic image are more informative than those from individual channels[6]. More recently, an adaptive threshold based on high frequency information was proposed for the interpolation of green pixels[21]. Colour demosaicking has also been achieved by considering the spectral and spatial sparse representations of images jointly[22]. All these techniques highlight the fact that the presence of edges should be taken into account while interpolating. This forms the basis of our paper in which we use the edge strength information from the mosaic image in a non-iterative manner for determining the relative participation of pixels while interpolating. The result is a linear filter that achieves interpolation through fuzzy memberships.

G_{00}	B_{01}	G_{02}	B_{03}	G_{04}	B_{05}	G_{06}
R_{10}	G_{11}	R_{12}	G_{13}	R_{14}	G_{15}	R_{16}
G_{20}	B_{21}	G_{22}	B_{23}	G_{24}	B_{25}	G_{26}
R_{30}	G_{31}	R_{32}	G_{33}	R_{34}	G_{35}	R_{36}
G_{40}	B_{41}	G_{42}	B_{43}	G_{44}	B_{45}	G_{46}
R_{50}	G_{51}	R_{52}	G_{53}	R_{54}	G_{55}	R_{56}
G_{60}	B_{61}	G_{62}	B_{63}	G_{64}	B_{65}	G_{66}

P_1	P_2	P_3
P_4	P_5	P_6
P_7	P_8	P_9

Figure 1. Bayer CFA Pattern and the 3 x 3 neighbourhood used to calculate the edge strength S.

2. PROPOSED FUZZY NON-LINEAR COLOUR DIFFERENTIAL CORRELATIVE INTERPOLATION FOR HIGH DETAIL IMAGES

There are a number of colour correlation based interpolation techniques which assume either colour ratio[8] or colour difference[5] to be constant. The latter technique which is called the colour differential correlative interpolation (CDC) gives excellent results for positive colour correlation but produces colour artifacts in the case of negative colour correlation or location of edge points. The non-linear CDC filter is used to reduce the artifacts that arise in the colour difference method[1]. The non-linear CDC filter involves a directed interpolation process with constant scrutiny of edge information and consequent selective participation of the neighborhood pixels in the interpolation. We avoid this constant scrutiny of edges by including all the pixels in the interpolation process and assigning a weight to each pixel based on its edge strength. The lesser the edge strength at a pixel the more is its participation in the interpolation process.

The proposed fuzzy non-linear CDC filter is described below. Authors defined the edge strength for a mosaic image, as defined by Kuno & Sugiura[2]. Consider a 3 x 3 neighbourhood of pixels labeled P_1-P_9 (Fig.1). Then the edge strength[2] at the center pixel P_5 is given by

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$$S = \frac{|P_1 - P_9|}{2} + \frac{|P_3 - P_7|}{2} + |P_2 - P_8| + |P_4 - P_6| \tag{1}$$

For any pixel k in the mosaic image, the edge strength computed using Eqn. (1) is S_k , k = 1, 2,…, M x N, where M x N is the size of the mosaic image. The fuzzy membership of the pixel k for participation in the interpolation process is given by

$$\mu_k = 1 - \frac{S_k}{\max\limits_{\forall k}(S_k)} \tag{2}$$

The fuzzy membership μ_k in Eqn. (2) has values in the range of 0 to 1. High membership indicates that k belongs to a smooth region (low edge strength S_k) and low membership indicates that k is an edge pixel (high edge strength S_k).

The fuzzy average of a set X with elements $x \in X$ having a set of associated memberships { μ } is defined as

$$\bar{\mu} = \frac{\sum_{x \in X} \mu x}{\sum_{x \in X} \mu} \tag{3}$$

Now we replace the averaging in the interpolation process of the non-linear CDC filter by the fuzzy averaging of the interpolating pixels using Eqn. (3), instead of checking iteratively whether the correlation is maximum along horizontal (H) or vertical (V) direction and applying the interpolation only in that direction[1]. Since each pixel is weighted by its membership, the participation of edge pixels in the negative correlation case is automatically reduced due to lower fuzzy memberships.

The steps of our fuzzy non-linear CDC filter method are outlined below on the lines of the process in[1] for the Bayer pattern in Fig. 1. Here the lower case letters are the interpolated signals and the upper case letters are the already existing ones in the mosaic image. Step 0 involves the computation of the gradients $divKv$ and $divKh$ in H and V directions respectively[1]. This step is omitted in our method since the participation of the interpolating pixels is determined automatically through fuzzy memberships and not through a rigorous *if-else* procedure.

Step 1: G plane interpolation on R and B planes

At the R_{32} pixel location,

$$g_{32} = R_{32} + (G_{32\varepsilon} - R_{32\varepsilon}) \tag{4}$$

The subscript ε in Eqn. (4) denotes low frequency information computed by fuzzy averaging as shown below.

$$G_{32\varepsilon} = \frac{\sum_{ij} \mu_{ij} G_{ij}}{\sum_{ij} \mu_{ij}}, ij \in 22, 31, 33, 42 \tag{5}$$

$$R_{32\varepsilon} = \frac{\sum_{ij} \mu_{ij} R_{ij} + 4\mu_{32} R_{32}}{\sum_{ij} \mu_{ij} + 4\mu_{32}}, ij \in 12, 30, 34, 52 \tag{6}$$

The edge pixels thus contribute less to the computation of the second term in Eqn. (4) which is the offset value. The G values at B pixel locations are similarly computed.

Step 2: R and B plane interpolation on G plane.

At the G_{22} pixel location,

$$r_{22} = G_{22} + (R_{22v\varepsilon} - g_{22v\varepsilon}) \tag{7}$$

where

$$R_{22v\varepsilon} = \frac{\sum_{ij} \mu_{ij} R_{ij}}{\sum_{ij} \mu_{ij}}, ij \in 12, 32 \tag{8}$$

$$g_{22v\varepsilon} = \frac{\sum_{ij} \mu_{ij} g_{ij}}{\sum_{ij} \mu_{ij}}, ij \in 12, 32 \tag{9}$$

Similarly at the G_{33} pixel location,

$$r_{33} = G_{33} + (R_{33h\varepsilon} - g_{33h\varepsilon}) \tag{10}$$

The subscripts h and v in Eqn. (10) and Eqn. (7) denote the low frequency information in horizontal and vertical directions respectively. The B values at all G pixel locations are similarly computed.

Step 3: Interpolation of R and B planes on B and R planes respectively.

At the B_{23} pixel location,

$$r_{23} = g_{23} + (R_{23\varepsilon} - g_{23\varepsilon}) \tag{11}$$

where,

$$R_{23\varepsilon} = \frac{\sum_{ij} \mu_{ij} R_{ij}}{\sum_{ij} \mu_{ij}}, ij \in 12, 14, 32, 34 \tag{12}$$

$$g_{23\varepsilon} = \frac{\sum_{ij} \mu_{ij} g_{ij}}{\sum_{ij} \mu_{ij}}, ij \in 12, 14, 32, 34 \tag{13}$$

The B values at all R pixel locations are similarly computed.

3. THE FUZZY BILINEAR INTERPOLATION FILTER FOR REAL TIME APPLICATIONS

Authors presents a simplified version method for faster processing. In this method we simply interpolate the colours in the same plane without adding any offset to the existing center pixel. This is equivalent to a fuzzification of the bilinear interpolation filter[11] method of colour demosaicking, which averages the colour samples without checking for any edges. The edge strength is used to compute the fuzzy memberships as in Eqn. (2). The fuzzy memberships obtained from the edge strength using Eqn. (2) constrain the contribution of edge pixels in the weighted averaging.

The steps of our fuzzy bilinear interpolation method are given below for the Bayer pattern in Fig. 1.

Step 1: G plane interpolation on R and B planes

At the R_{32} pixel location

$$g_{32} = \frac{\sum_{ij} \mu_{ij} G_{ij}}{\sum_{ij} \mu_{ij}}, ij \in 22, 31, 33, 42 \tag{14}$$

Step 2: R and B plane interpolation on G, B planes and G,R planes respectively.

At the G_{22} pixel location,

$$r_{22} = \frac{\sum_{ij} \mu_{ij} R_{ij}}{\sum_{ij} \mu_{ij}}, ij \in 12, 32 \tag{15}$$

At the B_{23} pixel location,

$$r_{23} = \frac{\sum_{ij} \mu_{ij} R_{ij}}{\sum_{ij} \mu_{ij}}, ij \in 12, 14, 32, 34 \tag{16}$$

The B values at all G and R pixel locations are similarly computed. In the case of the Bilinear interpolation filter the memberships in Eqns. (14)-(16) are equal to 1.

4. EXPERIMENTAL RESULTS

The experiments are conducted on the high definition images, 'Fungi', 'Insect', 'Painting', 'Fruits', 'Stones' downloaded from the web shown in Fig. 2, and also on state of the art databases – Berkeley (100 test images of size 481 x 321)[9], high resolution and high dimensional Landsat satellite images[17], 700 x 504 Nikon fluorescent microscopy images[18] and the 512 x 712 Kodak true colour loss less images[19]. For each image, the mosaic is obtained in the layout of the Bayer pattern in Fig. 1. The coding is done in MATLAB 7.9 on a 2.3 GHz Pentium processor. The PSNR and runtime of the proposed fuzzy bilinear interpolation filter (labeled as (k)) and the proposed fuzzy Non-linear CDC filter (labeled as (l)) are compared with a slew of state-of-the-art colour demosaicking methods namely,

(a) Nearest neighbor replication[12]
(b) Bilinear interpolation[11]
(c) Smooth hue transition interpolation[13]
(d) Pattern matching algorithm[14]
(e) Edge directed interpolation[15]
(f) Colour interpolation using Laplacian second order colour correction[7]
(g) Threshold based variable number of gradients[16]
(h) Gradient corrected linear interpolation[20]
(i) Edge strength based CFA interpolation[2] and
(j) Non-linear CDC filter[1].

The colour demosaicking results of the five high-definition images are shown in Table 1 for all methods. It is seen that for

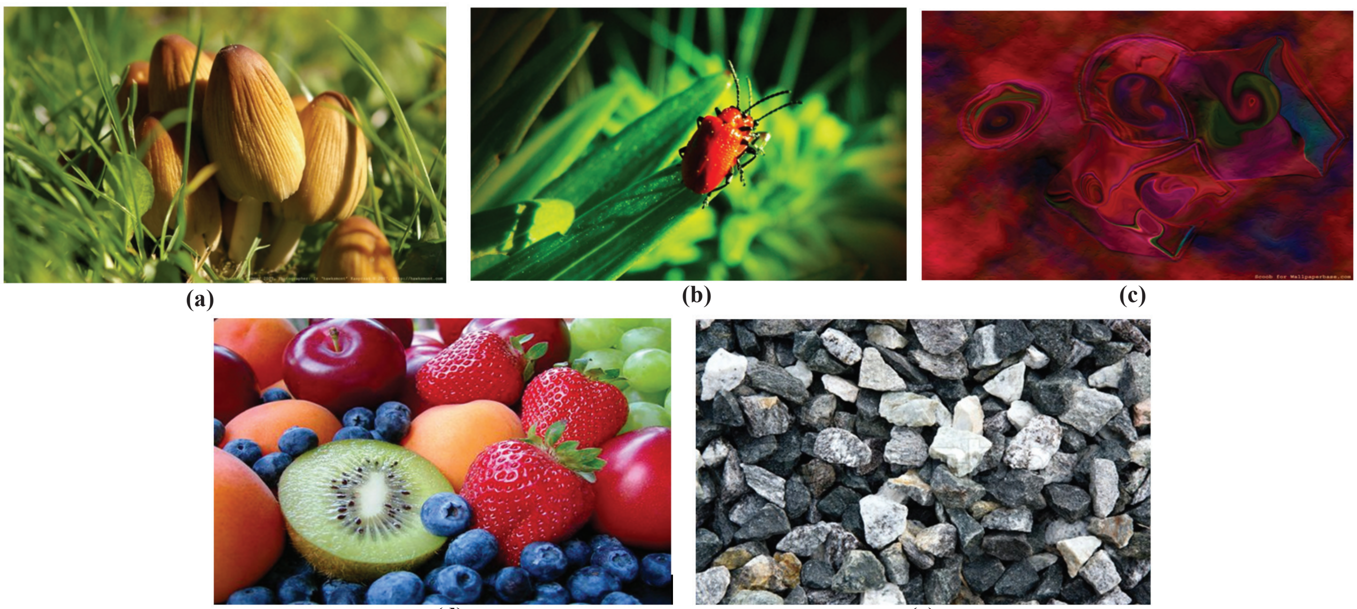
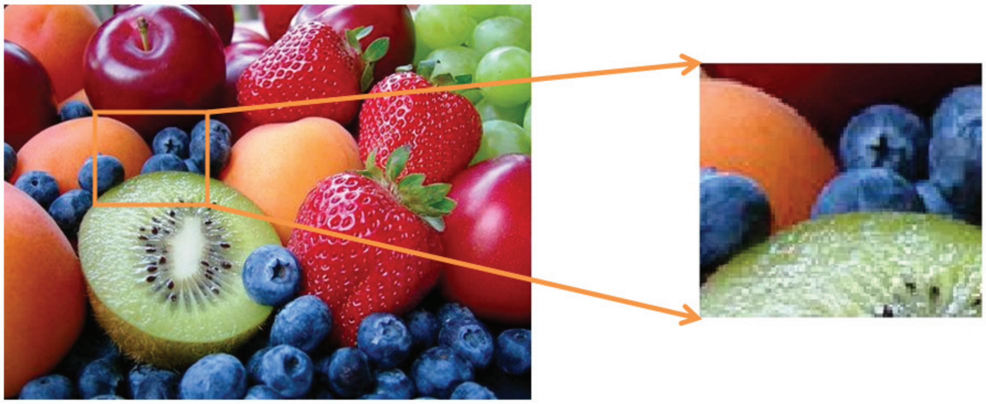


Figure 2. The high definition images used for the experimentation, (a) Fungi, (b) Insect, (c) Painting, (d) Fruits, (e) Stones.

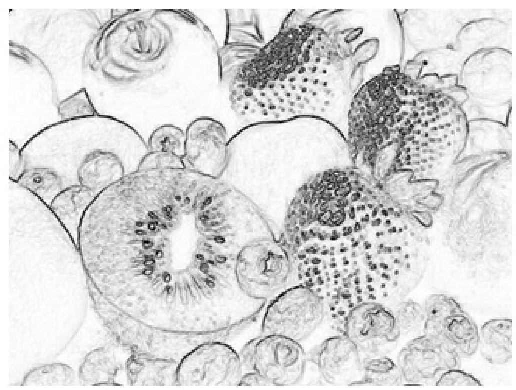
Table 1. Results of real-time colour filter array interpolation on the high definition images in Fig. 2 in terms of PSNR and running time in seconds.

Methods	Fungi 2560 x 1600		Insect 1680 x 1050		Painting 1024 x 768		Fruits 495 x 370		Stones 480 x 320	
	PSNR	Time	PSNR	Time	PSNR	Time	PSNR	Time	PSNR	Time
(a)	46.7	0.23	35.9	0.02	47.8	0.09	38.6	0.03	48.0	0.07
(b)	50.3	0.77	36.9	0.03	50.2	0.40	40.3	0.04	51.6	0.17
(c)	41.4	43.1	38.2	1.69	42.3	18.3	38.9	1.97	46.4	8.25
(d)	43.2	124.7	34.9	4.60	46.7	52.6	36.2	5.46	47.3	24.5
(e)	51.1	12.4	37.0	0.43	50.6	5.13	40.6	0.52	51.9	2.29
(f)	39.0	34.2	34.8	1.47	42.2	13.3	35.0	1.78	49.5	4.67
(g)	40.1	351.9	35.4	14.6	42.1	145.9	35.7	17.5	45.1	64.2
(h)	52.3	0.22	39.2	0.01	51.1	0.05	42.3	0.01	49.6	0.03
(i)	Too large computations									
(j)	54.0	58.1	39.4	1.93	51.5	23.2	42.3	2.41	49.3	10.3
(k)	50.9	26.8	37.0	0.94	50.5	11.2	40.6	1.12	51.9	5.36
(l)	53.5	65.7	40.1	2.46	52.0	29.7	42.8	2.91	50.0	12.6

all images except Fungi, the proposed fuzzy filters outperform the other methods, with our fuzzy bilinear interpolation filter (k) providing the lesser execution time, albeit at a reduced picture quality. The fuzzy bilinear interpolation filter however gives best results for the 'Stones' image where colour contrast and colour edges are few. The results for the Edge strength filter[2] are not included since the runtime (several hours for each image) for these images is too considerable for real-time applications. Fig. 3 shows the mosaic image and its edge strength map for the 'Fruits' image. A small segment of the 'Fruits' image, highlighted in Fig. 3, is used for visual comparison of the reconstructed results of all methods in Fig. 4. As observed, the fuzzy non-linear CDC filter (l) gives the best visual match to the original image in Fig. 3 and the highest PSNR in Table 2.



(a)



(b) **(c)**

Figure 3. (a) The original 'Fruits' image with a small section shown highlighted, (b) The original mosaic image, and (c) The edge strength map of the mosaic image.

Table 2. Results of real-time colour filter array interpolation on various datasets in terms of the (average PSNR ±Standard deviation, average time in seconds ± Standard deviation).

Methods	Berkeley images (100 images)		Landsat satellite images (23 images)		Nikon fluorescent microscopy images (24 images)		Kodak loss-less colour images (24 images)	
	PSNR	Time	PSNR	Time	PSNR	Time	PSNR	Time
(a)	40.2±1.2	0.008±0.004	39.0±2.6	0.08±0.05	41.8±1.8	0.02±0.02	40.1±1.8	0.04±0.005
(b)	44.0±2.2	0.09±0.03	41.1±3.6	0.4±0.22	42.2±2.1	0.07±0.012	41.2±2.1	0.13±0.01
(c)	42.5±2.3	1.91±0.28	39.1±2.0	15.9±8.7	41.8±2.2	3.6±0.09	41.0±2.2	4.6±0.2
(d)	37.8±1.8	5±0.4	37.5±2.0	56.1±29.2	41.7±1.5	9.8±0.46	37.6±1.1	10.6±0.3
(e)	44.7±2.6	0.5±0.07	41.5±3.8	5.5±3.0	44.3±2.2	0.92±0.04	42.3±2.2	1.1±0.08
(f)	36.1±3.1	1.6±0.17	36.7±2.2	12.6±6.8	40.2±1.2	2.0±0.31	36.6±2.0	4.4±0.7
(g)	37.2±2.2	15±2	36.2±1.7	129.5±68.2	39.4±1.4	24.9±2.4	35.9±1.7	48.4±4
(h)	45.6±2.1	0.006±0.001	43.7±3.9	0.05±0.02	43.3±2.2	0.01±0.0	44.4±2.3	0.03±0.02
(i)	46.0±2.3	228±34	Too large computations		42.6±2.1	275.0±17.5	44.8±2.3	403±60
(j)	45.0±2.0	2±0.11	44.2±4.0	18.7±9.6	43.0±2.1	4.3±0.08	46.0±2.4	6.9±0.1
(k)	44.3±2.5	0.95±0.06	41.3±3.8	14.2±7.5	44.4±.2.2	1.9±0.03	42.0±2.2	3.4±0.09
(l)	46.3±2.4	2.5±0.2	44.4±4.0	23.0±11.8	43.1±2.2	5.1±0.12	45.3±2.3	8.7±0.07

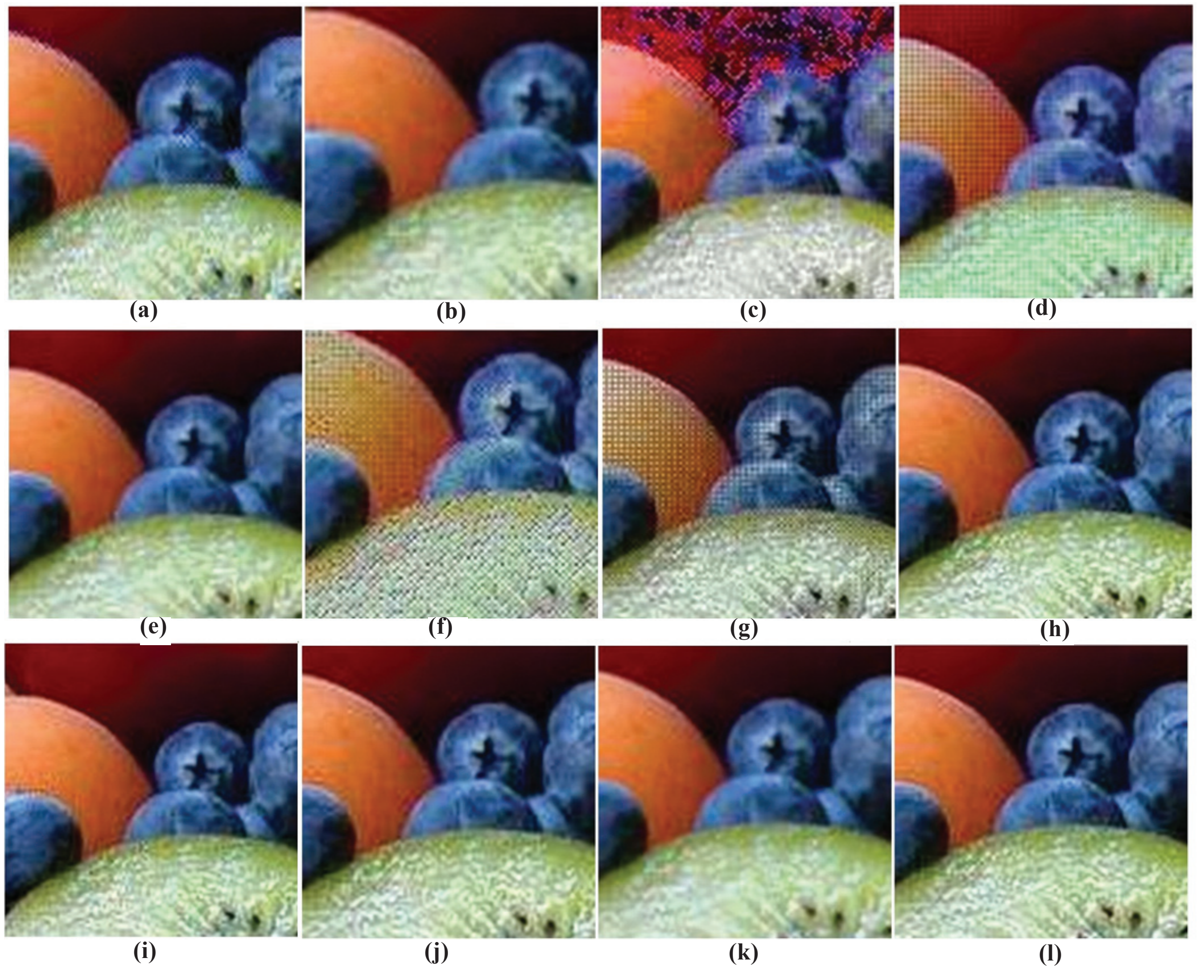


Figure 4. The reconstructed colour images for the highlighted section of Fruits image in Fig. 3 for the 12 colour demosaicking methods labeled (a) to (l) in the results section.

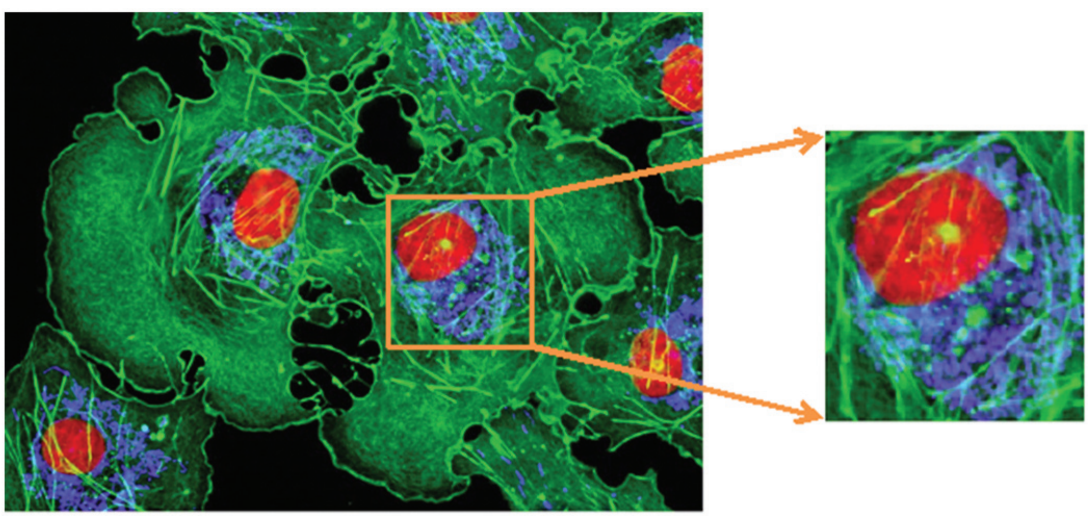


Figure 5. An example from the Nikon Microscopy database with a highlighted section shown for subsequent comparison of demosaicking results.

The results for the Berkeley, Landsat, Nikon Microscopy, and Kodak datasets are summarized in Table 2 for methods (a) to (l) and these once again ascertain the efficiency of the fuzzy colour demosaicking algorithms proposed in this paper in terms of the highest possible PSNR achieved at the lowest runtime. The proposed Fuzzy bilinear interpolation method is a good option for colour interpolation in real-time with acceptable visual quality, whereas for high resolution images the Fuzzy non-linear CDC filter can be relied on for obtaining highly efficient results in a very short time. Fig. 6 shows the interpolated results of the zoomed in image of the microscopy image shown in Fig. 5. The results indicate the best visual

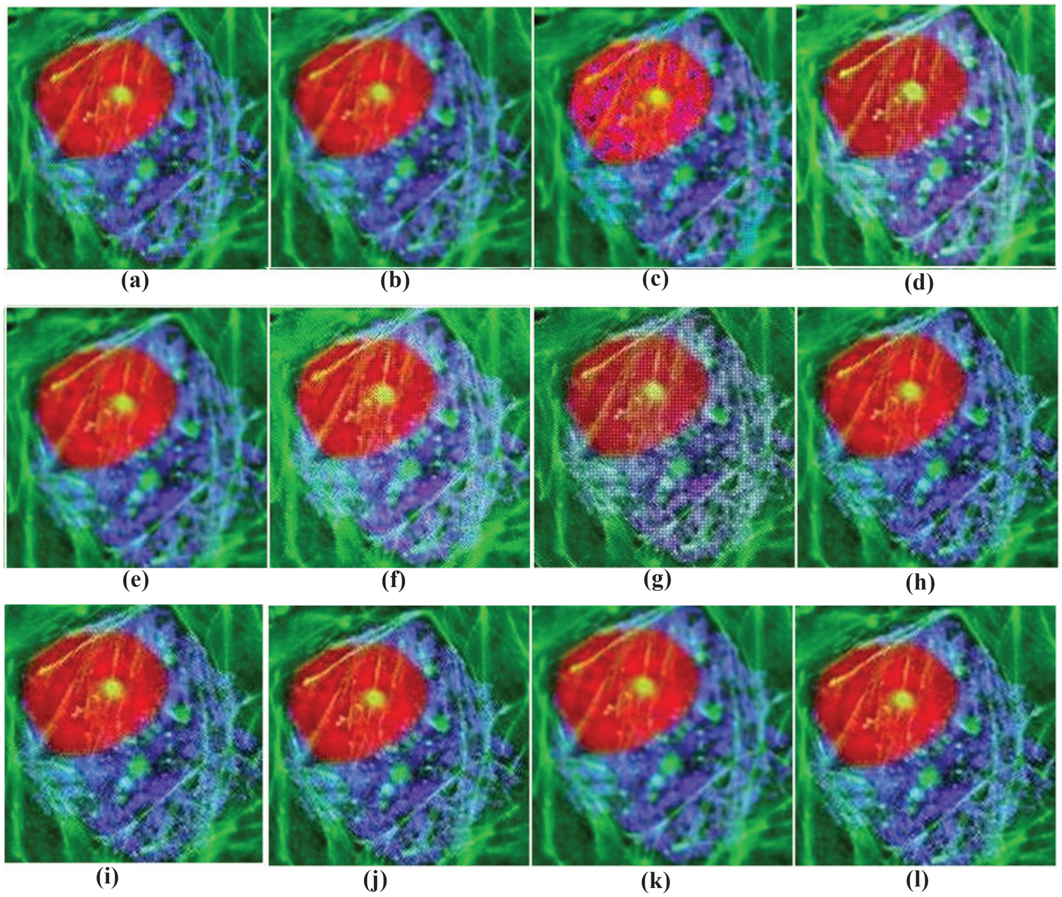


Figure 6. Results of 12 demosaicking methods (a)-(l) on an example from the Nikon Microscopy database the highlighted section in Fig. 5.

quality for the proposed fuzzy bilinear interpolation method as compared to all other methods. The Gradient corrected linear interpolation (method (h)) provides the lowest runtime but its PSNR is relatively low. The Fuzzy bilinear interpolation is found to excel for the Microscopy images in terms of highest PSNR with an average execution time of only 2 s. The Fuzzy non-linear CDC method is found best for the high resolution satellite images and marginally close to the non-linear CDC filter for the Kodak images, outperforming all other methods in a consistent manner.

5. CONCLUSION

In this study, authors fuzzify the non-linear CDC colour filter array interpolation and the bilinear interpolation techniques for colour demosaicking. The fuzzy memberships used are derived from the edge strength map of the mosaic image. We observe a rise in PSNR values and reduction in execution time for high resolution images where the edge information is significant.

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