Innovative Color Interpolation Using Fuzzy Logic and Linear Regression

Jyh-Jiun Lee, Yu-Sheng Tsai, Yi-Ching Liaw, Chia-Lun Chen, Chia-Hung Cheng, and Shih-Chieh Chen,
Opto-Electronics & Systems Laboratories, Industrial Technology Research Institute, Taiwan
Yi-Bin Lu, Department of Electrical Engineering, Chung Cheng Institute of Technology, National Defense University, Taiwan

Abstract

To reduce the cost of digital cameras, the color filter array (CFA) is usually coated upon a single-chip image sensor. Each pixel of the image sensor can sense only one of the R, G and B colors under CFA. The two missing colors of a pixel are estimated using the CFA interpolation algorithm. The interpolation algorithm may generate color distortion and degrade the quality of interpolated images. In this paper, we propose a new algorithm "fuzzy logic and linear regression method (FLLRM)" to solve this problem.

We use fuzzy logic method based on the effect between pixels to avoid color distortion around the edges. The linear regression method is used to process the interaction effect among R, G and B channels. The proposed method can successfully eliminate false color, color moire, aliasing and color shifts in the full color camera output. Finally, we implement our method on the digital camera platform that is designed by Industrial Technology Research Institute (ITRI). The processed image shows a very good quality, which also demonstrates our approach is a better CFA interpolation algorithm than the previous processed methods.

1. Introduction

To reduce the cost of digital cameras, the color filter array (CFA) is coated upon a single-chip sensor. Figure 1 shows the Bayer pattern[1], which is one of the most frequently, used CFAs and is used in this paper.

An example of a color image and its Bayer pattern CFA image is shown in Figure 2. As shown in Figure 2, we can see that there is only one color being sensed in each pixel of the CFA image and two missing colors must be estimated. The process of generating missing colors is called CFA interpolation.

There are many CFA interpolation methods available. Bilinear interpolation[2] is the simplest method that estimates the missing colors using the average value of its nearest neighboring pixels. Using bilinear interpolation, the interpolated images will be blurred due to higher frequencies are filtered out. To solve this problem, some other interpolation methods are proposed to improve the edge quality. The edge-sensing methods[3,-7] classify pixels into several categories using edge orientation and different interpolation schemes are applied to interpolate the missing colors for different categories. Due to the existence of high correlation between the R, G, and B channels, the correlation between different channels are used to interpolate the missing colors by some researchers.[2,6-8]

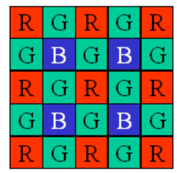
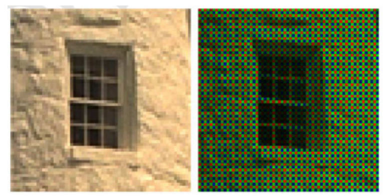


Figure 1. Bayer pattern



(a) Color image *(b) Bayer pattern CFA image*

Figure 2. An example of a color image and its Bayer pattern CFA image

(a) Original image *(b) Interpolated image*

Figure 3. An example of an image with artifacts caused by CFA interpolation

Tsai, Acharya and Ray proposed a method "Adaptive fuzzy color interpolation.[9]" for CFA images in 2002. The method utilizes the fuzzy membership assignment as a weighting factor along with the concept of smooth hue transition to estimate the missing colors in each pixel.

However, the CFA interpolation may generate color distortion and artifacts appear in the edge and texture areas of interpolated images. Figure 3 shows an example of an image with artifacts due to CFA interpolation. In Figure 3, we can see the artifacts appear in the wall of the house (left side) and in the fence (right side) of the interpolated image. The appearance of artifacts degrades greatly the quality of interpolated images.

To improve the quality of interpolated images, the estimation errors have to be reduced. In this paper, we propose a new algorithm "fuzzy logic and linear regression method (FLLRM)" to solve this problem. In our experiments, we find that the estimation error of interpolated R and B colors could be reduced dramatically by giving a better G channel for those interpolation methods using correlations between R, G and B colors. That is, the quality of interpolated images using CFA interpolation can be effectively improved by providing a better G value. To improve the G channels of interpolated images, we attempt to use fuzzy logic method to reduce the edge distortion between the pixels of G channels. The fuzzy logic method can provide a better G value. After getting a better G value, we can use the linear regression method to find the relationships between R, G and B channels. We apply the relationships to modify some missing R and B colors. Finally, we use fuzzy logic method to interpolate both R and B channels. From our experiments, we find that the proposed algorithm can effectively improve the quality of interpolated images.

This paper is organized as follows. In Section 2, we review the CFA interpolation algorithm, which is reference to interpolate the CFA images in the paper. In Section 3, the proposed fuzzy logic algorithm for improving the G channels of interpolated images is described. We present the method of applying the linear regression method to modify the R, B channels, and a fuzzy logic method to interpolated R and B colors. The proposed algorithm is implemented and verified on a digital camera developed by ITRI. The experimental results are presented Section 4. Finally, conclusions are given in Section 5.

2. CFA Interpolation Algorithm

In this paper, a CFA interpolation algorithm proposed by Pei and Tam[6] is used to interpolate the CFA image due to its good performance and simplicity. The algorithm is briefly described below.

Step 1: G channel interpolation. To find the missing G value, the K_R or K_B values of the neighboring pixels must be computed first, where K_R and K_B are defined as follows:

$$K_R=G-R \quad (1)$$

$$K_B=G-B \quad (2)$$

For a pixel has only the value of R, the missing G value is interpolated using the correlation between R and G channels. In this case, the K_R values of the neighboring pixels are used to estimate the missing G value. For example, the missing G value, G7, at the pixel location of R7 in Figure. 4 is calculated by Equation (3).

$$G7 = R7 + \frac{(K_R 3 + K_R 6 + K_R 8 + K_R 11)}{4} \quad (3)$$

where $K_R3=G3-R3=G3 - (R1+R7)/2$,
$K_R6=G6-R6=G6 - (R5+R7)/2$,
$K_R8=G8-R8=G8 - (R7+R9)/2$,
$K_R11=G11-R11=G11 - (R7+R13)/2$.

The interpolation process of estimating the missing G value for a pixel with only the B value is similar.

Step 2: R channel and B channel interpolations. Once the G channel is estimated, the missing R and B values can be estimated using the interpolated G channel. The process of estimating missing R and B values is similar to the G channel interpolation. K_R and K_B are used to interpolate the missing R and B values, respectively. For examples, R3 at the pixel location of G3 and B7 at the pixel location of R7 in Figure 4, are determined using Equations (4) and (5), respectively.

$$R3 = G3 + \frac{(K_R 1 + K_R 7)}{2} \quad (4)$$

$$B7 = G7 + \frac{(K_B 2 + K_B 4 + K_B 10 + K_B 12)}{4} \quad (5)$$

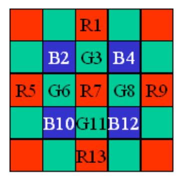


Figure 4. An example of Bayer pattern

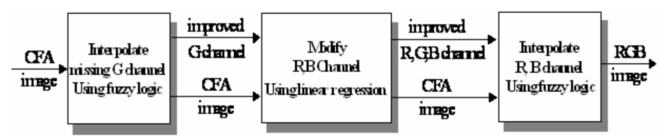


Figure 5. The improving process of interpolated CFA images

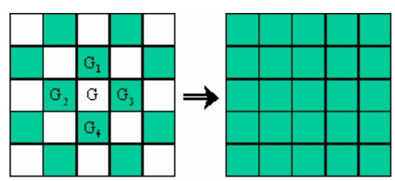
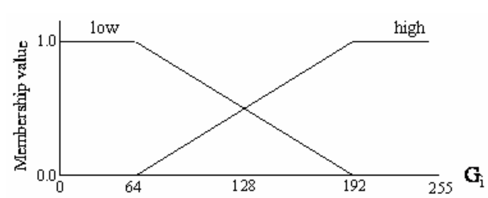
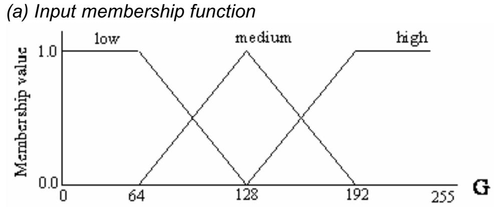


Figure 6. An example for fuzzy logic pattern



(a) Input membership function



(b) Output membership function

Figure 7. Membership function

3. Color Improvement of Interpolated Color Filter Array Images Using FLLRM

In this section, we will describe how to use FLLRM to improve the interpolated images. The process is shown in Figure 5.

As shown in Figure 5, the missing G channel of a CFA image is interpolated using fuzzy logic method firstly. Then, the computed G channel and the CFA image are used as the inputs to modify part of R and B channels. We modify part of R and B channels by using the linear regression method. In the last, the rest of R and B channels can be interpolated using fuzzy logic method the same as in the first procedure. In the following, we will introduce FLLRM approach.

3.1 Using Fuzzy Logic to Interpolate Missing G Channel

The values of G channel are interpolated by using fuzzy logic method. The four inputs, G_1 G_2 G_3 G_4, are used as bases as shown in Figure 6. To determine the G_i input membership function, fuzzy rules and G value output membership function, we find an optimized solution according to lots of experiment results. Since we pay much attention to the color information for both high and low brightness, we define "high" and "low" membership function as G_i input membership function as in Figure 7(a). If G_i is greater than 192, the membership function is "high". The function value decreases while G_i is reduced gradually and the function value is going to 0 when G_i is reduced to 64. In the same way, if G_i is less than 64, the membership function is "low". Also, the function value is decrease to 0 while G_i is increasing to 192.There are three G value output membership functions that are low, medium and high as in Figure 7(b). The output membership function is "high" if the G value is greater than 192, "low" if G value is less than 64, and "medium" if G value is equal to 128.

Then we define the fuzzy rules (see the Table1) based on four input values, G_1 G_2 G_3 G_4, and under considering the edge effect between pixels.

Table 1: The Fuzzy Rules

Rule	If				Then
	G_1	G_2	G_3	G_4	G
1	high	high	high	high	high
2	high	high	high	low	high
3	high	high	low	high	medium
4	high	high	low	low	high
5	high	low	high	high	high
6	high	low	high	low	medium
7	high	low	low	high	medium
8	high	low	low	low	low
9	low	high	high	high	high
10	low	high	high	low	medium
11	low	high	low	high	low
12	low	high	low	low	medium
13	low	low	high	high	medium
14	low	low	high	low	low
15	low	low	low	high	low
16	low	low	low	low	low

We use "And method" for input variables of the "If Part" in all rules. The "Cut method" is used for the "Then Part" for each rule. Then the "Or method" is used between rules. Finally, for the defuzzification, we use the Center-of-Area (COA) method proposed by Teng and Tzeng[10] to find the optimal result.

According to the procedure mentioned in this section, we can interpolate all the missing pixel values of the G channel.

3.2 Using Linear Regression to Modify R and B Channel

We calculate the missing pixel values of G channel according to the proposed method in section 3.1. After that, we modify R and B channel by using the following formula.

$$G=m_0R+m_1B+m_2 \tag{6}$$

The element m_0, m_1 and m_2 can be obtained through linear regression. Some RGB values should be given as an initial condition. We take a picture for a color chart that with some large area color patches, using the testing digital camera under D50 lighting. The RGB values of color patches are then obtained from CFA image.

According to linear regression, we have an estimate G value (G_e) defined by

$$G_e = [m_0 \ m_1 \ m_2] \begin{bmatrix} R \\ B \\ 1 \end{bmatrix} \tag{7}$$

In order to optimize the estimated G value, we can find a matrix M_{1*3} to minimize the difference $\Delta G=G-G_e$.

For n set R, G, and B values($R(i)$ 、$G(i)$、$B(i)$；i=1~n), the cost function *Cost_G* is the mean square error defined as follows:

$$Cost\_G(m_j | j=0\sim3) \equiv \sum_{i=1}^{n} \left(G(i)-Ge(i)\right)^2 \tag{8}$$

G(i) : original value of G channel for i-th color patch
$G_e(i)$: estimated value of G channel for i-th color patch
m_j : element of the matrix

To find the minimum of the cost function, we compute the partial differentiation versus each matrix element m_j and set it to be 0.

$$\partial Cost\_G(m_j)/\partial m_j = 0 \tag{9}$$

Then we can obtain a matrix to have a least cost function. The matrix element m_j can be find in the following equation.

$$[m_0 \, m_1 m_2]^T = A_{3\times3}^{-1} \cdot B_{3\times1} \tag{10}$$

where matrix A is given as

$$a(i,j)=\sum_{l=1}^{n} c_i(l)\cdot c_j(l) \tag{11}$$

matrix B is given as

$$b(i)=\sum_{l=1}^{n} G(l)\cdot c_i(l) \tag{12}$$

$c_0 \sim c_2$: input coefficient
$m_0 \sim m_2$: element of matrix
G(i): original G value of i-th color patch

The matrix is computed. Since all pixel values of G channel is obtained as mentioned in section 3.1 and some pixel values of B channel is known, the relative pixel values of R channel can be derived as the following formula.

$$R = (G-m_1B-m_2)/m_0 \tag{13}$$

Figure 8 shows the result. Most of the pixel values of R channel are obtained.

In the same way, the unknown values of B channel relative to the same pixels of R channel can be obtained by

$$B = (G-m_0R-m_2)/m_1 \tag{14}$$

The result is shown in Figure 9.

3.3 Using Fuzzy Logic to Interpolate the Rest of R Channel and B Channel

The modified R and B channel are continued to be interpolated using fuzzy logic method. The four inputs, R_1 R_2 R_3 R_4, are used as bases. In the same method as section 3.1, we derive the fuzzy rules based on the four input values to find the value of missing R component. Also, the values of missing B components are computed in the same way. So we obtain RGB values of the whole image as shown in Figure 10.

According to the procedure mentioned in this section, all the pixel values of R, G and B channel are obtained.

4. Experimental Results

To demonstrate the performance of the proposed algorithm, the proposed "FLLRM" algorithm is verified on a digital camera platform. The method described in section 2 is also implemented on the same platform to compare with our method. The test digital camera system is developed by ITRI. The digital camera contains an optical low-pass filter, and the major components of the platform are shown in Table2 and Figure 11.

The design goal of this project is to develop a processing core for high quality video as well as general still image processing. The original system uses an external Intel Strong ARM as the host processor, and uses hardwired functional blocks in the image pipeline with interface using proprietary bus protocol. Our algorithm is programmed on FPGA.

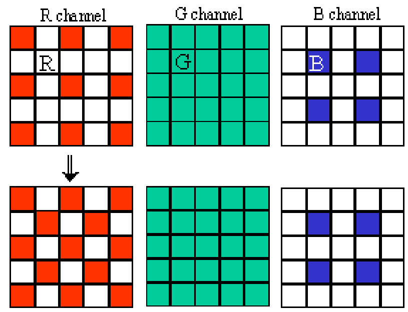


Figure 8. The result of modified R channel

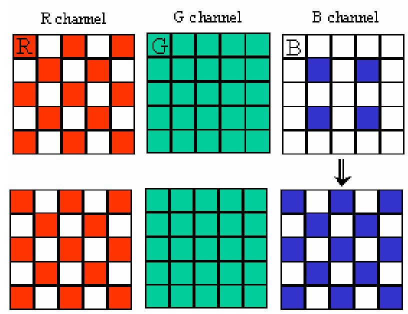


Figure 9. The result of modified B channel

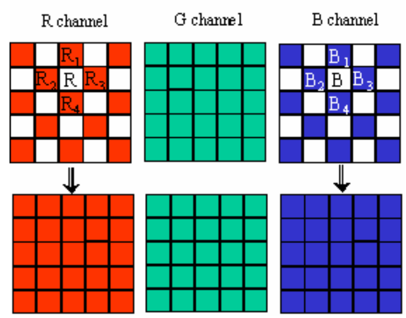


Figure 10. The result of modified B channel

Table 2:

Num.	Component
1	4 Mega Pixels CCD
2	ARM9EJ-S 175 MHz core
3	16K I-cache, 16K D-cache
4	On-chip 16K RAM and 8K ROM
5	108 MHz up to 256MB SDRAM
6	2 SDRAM DMA channels

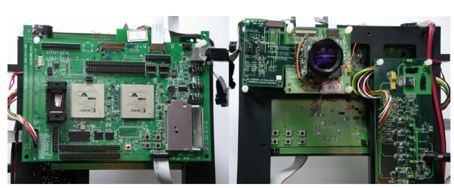


Figure 11. The hardware Architecture of digital camera platform

4.1 Find the Relationships between R, G and B Channels

In the proposed method, the relationship among R, G and B channel is

$$G_e = m_0 R + m_1 B + m_2 \quad (15)$$

It is very important to find optimal factors m0、m1 and m2. According to section 3.2, we have to take picture for a color chart with some color patches using the test camera first. In the experiment, the color chart is GretagMacbeth ColorChecker and the light source is D50. Then we get 24 RGB values of color patches from CFA image, as shown in Figure 12. The factors m0、m1 and m2 can be obtained according to linear regression. The relationship among R, G and B channels is:

$$G_e = 0.39R + 0.665B - 6.114 \quad (16)$$

Table3 shows the 24 RGB values of color patches. The estimated G value (G_e) and the difference (ΔG) between G and G_e are also shown in Table3 and Figure 13.

Table 3: Experiment Results

Num.	R,G,B	G_e	ΔG
1	55,38,36	38.93	0.93
2	155,111,97	118.62	7.62
3	59,77,94	79.77	2.77
4	45,51,40	37.9	13.1
5	88,89,114	104.05	15.05
6	85,147,139	119.61	27.39
7	162,80,49	89.52	9.52
8	46,57,96	75.86	18.86
9	142,63,56	86.82	23.82
10	47,33,45	42.29	9.29
11	111,130,74	86.21	43.79
12	172,112,57	98.86	13.14
13	31,39,74	55.43	16.43
14	55,86,61	55.87	30.13
15	119,44,38	65.67	21.67
16	203,155,80	125.96	29.04
17	138,70,86	105.23	35.23
18	45,89,115	87.65	1.35
19	252,253,251	255	2
20	175,181,178	180.68	0.32
21	112,117,115	113.75	3.25
22	67,71,71	67.04	3.96
23	40,39,43	38.02	0.98
24	23,19,24	18.7	0.3

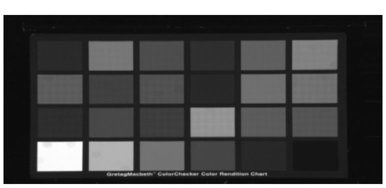


Figure 12. The CFA image of GretagMacbeth ColorChecker

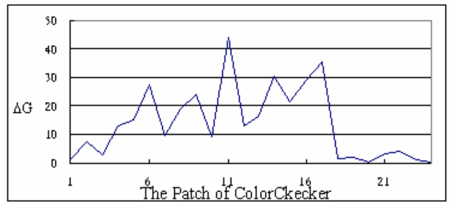


Figure 13. The difference value(ΔG) between G and G_e

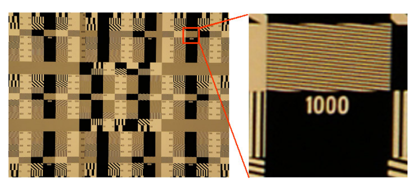
4.2 Results

To demonstrate the performance of the proposed algorithm, the proposed "FLLRM" algorithm is verified on a digital camera platform. The method described in section 2 is also implemented on the same platform to compare with our method. The test digital camera system is developed by ITRI.

Figure14 to Figure19 (a) show the results of our method, and Figure14 to Figure19 (b) are the results of the effective color interpolation method by Pei and Tam (P&T). From the images processed by our method, it is obviously that the false color, color moire, aliasing and color shifts are much less than the results of P&T. The experiment demonstrates much better image quality by using the proposed algorithm.

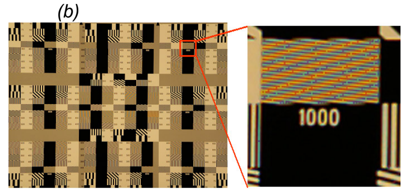
5. Conclusion

In this paper, we present a new algorithm that can be used to improve the interpolated colors of CFA images. We use fuzzy logic method which applied the relationship between pixels to avoid color distortion around the edges. The linear regression method is used to optimize the interaction effect among R, G and B channels. We also implement the algorithm on ITRI's digital camera to demonstrate the performance. The false color, color moire, aliasing and color shifts in the full color camera output are successfully eliminated. It shows a very good performance improving the interpolated colors of CFA images.



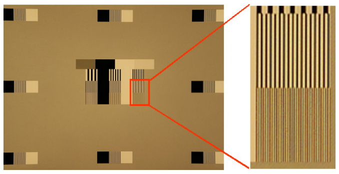
(a) Result of FLLRM

(b)

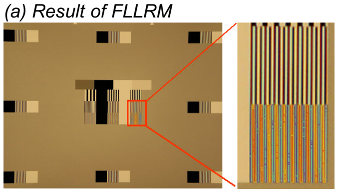


(b) Result of P&T

Figure 14. Aperture Resolution chart

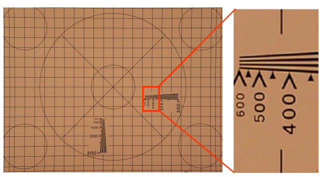


(a) Result of FLLRM

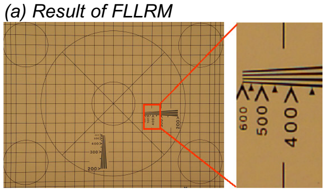


(b) Result of P&T

Figure 15. EIAJ Test chart-B2

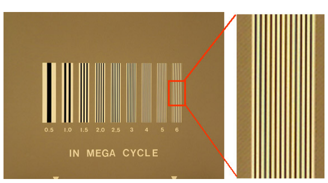


(a) Result of FLLRM

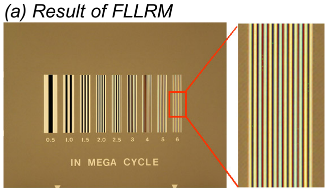


(b) Result of P&T

Figure 16. EIAJ Test chart-1

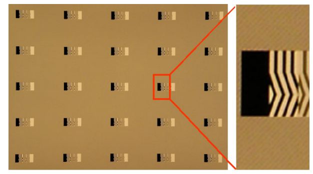


(a) Result of FLLRM

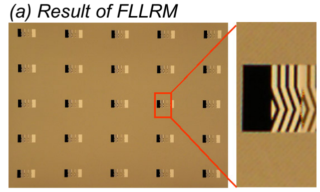


(b) Result of P&T

Figure 17. Resolution chart (In Mega Cycle)



(a) Result of FLLRM



(b) Result of P&T

Figure 18. Half-tone Resolution chart

Acknowledgments

The authors would like to thank the Ministry of Economic Affairs of the Republic of China for financially supporting this work.

References

1. Bayer, B.E., Color imaging array, U.S. Patent, 3, 971, 065.(1976).
2. Adams Jr., J.E., Interactions between color plane interpolation and other image processing functions in electronic photography. Proc. SPIE 2416, pg.144-151.(1995).
3. Jensen, K., Anastassiou, D., Subpixel edge localization and the interpolation of still images. IEEE Trans. Image Process. 4 (3), pg. 285–295.(1995).
4. Allebach, J., Wong, P.W., Edge-directed interpolation. Proc. IEEE Int. Conf. Image Process. 3, pg. 707-710.(1996).
5. Wu, X.-L., Choi, W.K., Color restoration from digital camera data by pattern matching. Proc. SPIE 3018, pg. 12-17.(1997).
6. Pei, S.-C., Tam, I.-K., Effective color interpolation in CCD color filter array using signal correlation. Proc. IEEE Int. Conf. Image Process. 3, pg. 488-491.(2000).
7. Li, X., Orchard, M.T., New edge-directed interpolation. IEEE Trans. Image Process. 10 (10), pg. 1521-1527.(2001).
8. Adams Jr., J.E., Design of practical color filter array interpolation algorithms for digital cameras. SPIE 3028, pg. 117–125.(1997).
9. Adaptive fuzzy color interpolation, Ping-sing Tsai, Tinku Acharya and Ajay K. Ray, Journal of Electronic Image, Vol. 11, Issue3, pg.293-305.(2002)
10. Yen, John and Langari, Reza, "Fuzzy Logic Intelligence Control & Information", Prentice Hall, Chap. 3, pg. 57-87.(1999).

Author Biography

Jyh-Jiun Lee is current working in Digital Video Imaging Department of Digital Imaging Technology Division at Opto-Electronics and Systems Laboratories of Industrial Technology Research Institute. He is also studying for Ph.D in Graduate School of National Defense Science of Chung Cheng Institute of Technology, National Defense University now. His interests include color management system, image quality, and color image processing. He completed his master degree in electric engineering department from Chung Cheng Institute of Technology, National Defense University in 1997.