A New Near-lossless Image Compression Method in Digital Image Sensors with Bayer Color Filter Arrays

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Abstract—**This paper presents a new method for near-lossless image compression for digital colorful image sensors with Bayer Color Filter Arrays (CFAs). In this method, the captured CFA raw data is first smoothed by low-pass filters followed by down-sampling and then compressed directly before full color interpolation which introduces redundancy. Assuring high image quality, the method can provide higher compression ratio and lower complexity than conventional image compression methods and other existing similar methods. The Composite Peak Signal to Noise Ratio (CPSNR) of decompressed image is larger than *51dB*.**

Index Terms—**Bayer CFA, medical image processing, near-lossless, image compression, and quincunx pattern.**

I. Introduction

In most of conventional colorful image sensors, the captured data with CFA pattern is interpolated into a full color image and then the interpolated data is processed and compressed as shown in Fig.1(a). Several new methods based on the scheme illustrated in Fig.1(b) have been reported to avoid data redundancy by moving compression operation before color interpolation [1-3]. Some good results have been obtained. However, all those methods are proposed for lossy compression and not suitable for near-lossless compression except 'structure conversion' method [3].

This paper presents a new near-lossless compression method based on the scheme of Fig 1(b), which has higher image compression ratio and lower computational complexity with high quality ($CPSNR \geq 51dB$) than conventional image compression methods and 'structure conversion' method[3]. This method can be applied in the fields required for high image quality, such as medical image processing field. There are several different color filter arrays (CFAs) in digital image sensors, but the Bayer CFA [4], as shown in Fig.2, is the most popular. The proposed method only considers the Bayer CFA, but it can be easily expanded to other CFAs. In this paper, the implementation precision is *8*-bit and the measure of quality, CPSNR, is defined in equation (1). where I_1 and I_2 are the original and reconstructed image with height of H and width of W, respectively and are expressed in integer values between *0* and *255*, x and y are the locations of the pixels, and i represents the color plane.

$$CPSNR = 10\log_{10}\left(\frac{255^2}{\frac{1}{3HW}\sum_{i=1}^{3}\sum_{x=1}^{W}\sum_{y=1}^{H}\left(I_1(x,y,i)-I_2(x,y,i)\right)^2}\right) \quad (1)$$

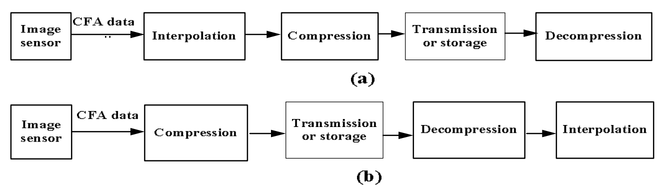

Fig. 1. Block diagrams of compressed schemes in a image sensor: (a) conventional method, interpolation before compression, (b) new method, interpolation after compression.

G	B	G	B
R	G	R	G
G	B	G	B
R	G	R	G

Fig. 2 Bayer pattern Color Filter Array (CFA).

II. Proposed Image Compression Method

A. Method Structure

Unlike other methods [2][3], in our method, CFA data is low-pass filtered directly in RGB space because the conversion from RGB space to YCbCr space results in the loss of image quality and increases computational complexity. The structure of the our method is shown in the Fig.3(a).

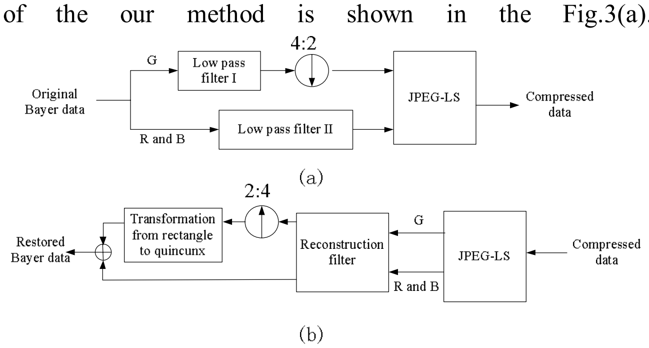

Fig.3. Block diagrams: (a) The proposed compression algorithm without the transformation from RGB to YCbCr, and (b) corresponding decompression algorithm.

G component of Bayer data is low-pass filtered followed with down-sampling. R and B components are processed with low-pass filter II. The implementation precision of both filters is *8*-bit. It is noted that the down-sampling (4:2) implements

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the transformation operation of G component from quincunx to rectangular array. Lastly, three components are compressed by JPEG-LS. Although the introduction of the low-pass filter leads to very small loss of high frequency, a good compression ratio comes out with high fidelity. The corresponding decompression method is shown in Fig.3(b). In this decompression structure, three components have the same reconstruction filter, which makes the decompression implementation simpler.

B. Method Description

There are more high frequency components in the horizontal direction and vertical direction of the Bayer CFA data than that in the full color image data, which is disadvantageous to image compression. If all blank points are removed directly and then the left points are emerged into a rectangle, many false high frequencies will be generated. In order to avoid the generation of those unwanted high frequencies, quincunx G component and rectangle R and B components are filtered respectively as follows:

1) G component

A low-pass filter for G component is applied before the transformation from quincunx to rectangle. The low-pass filter should have good reversibility so that perfect image quality can be assured after reconstruction. The low-pass filter I for G component uses an impulse response as follows:

$$H_{cg} = \frac{1}{4}\begin{bmatrix} 0 & 1 & 0 \\ 1 & 4 & 1 \\ 0 & 1 & 0 \end{bmatrix} \qquad (2)$$

Thus, the filtering procedure can be described in equation(3).

$$O_{m\times n} = I_{m\times n} \otimes H_{cg} \qquad (3)$$

Here, ‘$\otimes$’ is a convolution operator, and $I_{m\times n}$ denotes the $m \times n$ matrix of original CFA data, $O_{m\times n}$ denotes the matrix of the filtered CFA data.

The procedure before encoding of JPEG-LS is described in Fig.4. The 8×8 size of CFA data is assumed, where ‘●’ and ‘◍’ represent original pixels of odd columns and even columns respectively. ‘○’ represents the pixel which is generated from the original blank point, i.e. smoothed by the low-pass filter. ‘◌’ represents the virtual pixel which is used to compute the boundary pixels in the filtering operation. The virtual pixels of upper boundary are got from the first even row, i.e., the second row. The virtual pixels of bottom are equal to the original pixels of the second last row, i.e., the pixels of the seventh row. In this method, the smooth filter is applied to ‘○’ elements firstly, and then down-sampling operation is realized by the way that the first column and the fourth column are removed in every four columns. For example, in Fig.4, after filtering operation, the filtered pixels ‘○’ are got. Then the second, third, sixth and seventh column are down-sampled as well as the left columns are removed. Those down-sampled columns are emerged into a rectangle shape, which is the transformation operation of G component from quincunx to rectangle. Lastly, those rectangular data are compressed by JPEG-LS. The smooth filter reduces high frequency contents not only in the vertical direction but also in the horizontal direction.

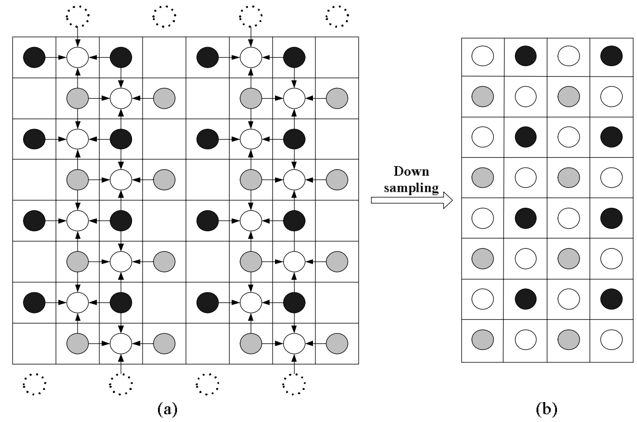

Fig. 4. Smooth filtering operation and down-sampling operation.

To assure the state-of-the-art reconstruction quality, the data decompressed by JPEG-LS decoder is processed by a reconstruction filter. Then the data is up-sampled by two blank columns. Last, rectangular data are transformed into quincunx data. The reconstruction filter consists of two 3×3 impulse response arrays, i.e. the odd columns and even columns use matrix(3) and matrix(4) respectively.

$$H'_{bre} = \begin{bmatrix} 0 & -1 & 0 \\ 0 & 4 & -1 \\ 0 & -1 & 0 \end{bmatrix} \quad (4), \qquad H'_{bro} = \begin{bmatrix} 0 & -1 & 0 \\ -1 & 4 & 0 \\ 0 & -1 & 0 \end{bmatrix} \quad (5)$$

The reconstruction operations are shown in Fig.5. Here, ‘⊗’ denotes the pixel which is reconstructed. The first step is that the pixels ‘○’ in odd column are filtered by 3×3 matrix (4) and the pixels ‘○’ in even column are filtered by 3×3 matrix(5). The filtered data ‘⊗’ are got as illustrated in Fig.5(b). Then the data are up-sampled by inserting two blank columns to the left and right sides of every two columns respectively. Lastly, the filtered pixels ‘⊗’ are shifted left or right one grid to restore G component of Bayer data in transformation operation as illustrated in Fig.5(c).

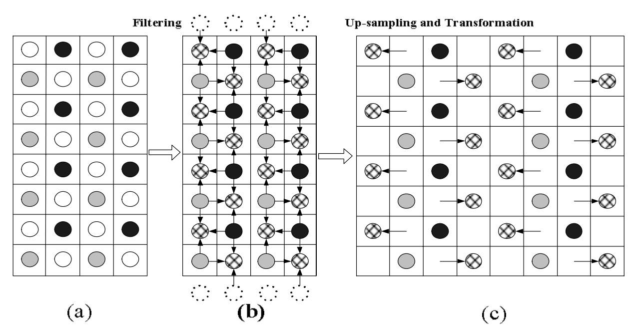

Fig. 5. Reconstruction filtering, up-sampling and transformation of G component from rectangle to quincunx.

2) R and B components

Because original data of R and B components are rectangular shape, there is no transformation of shape in the process of R and B components. In order to assure reconstruction quality, R and B components of CFA data are divided into two groups which are shown in Fig.6. Here, pixels ‘×’ represent the original pixels of the first group in which the data are not filtered but compressed directly for perfect reconstruction, and pixels ‘+’ denote the original pixels of the second group in which the pixels will be filtered, and ‘**o**’ denotes the filtered pixels, and ‘⁙’ denotes the virtual pixels which are used for the filtering operation of boundary pixels. The virtual pixels of the top row equal to that of the second row, and the virtual pixels of the bottom row equal to that of the second last row.

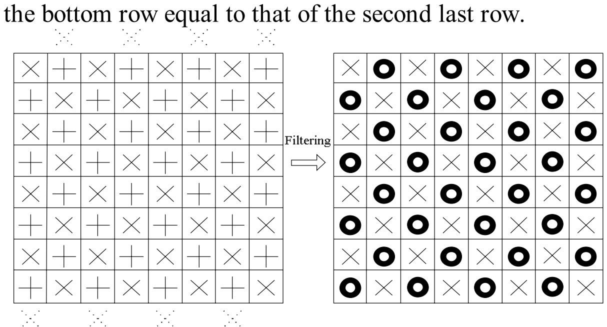

Fig.6. Division and filtering of R and B components of CFA data.

The pixels of the second group to be filtered, ‘+’, consist of two parts, odd rows of pixels and even rows of pixels, which are filtered by two different filters. The filters of odd columns and even columns use respectively the following impulse responses of equation (6) and (7):

$$H_{bre} = \frac{1}{4}\begin{bmatrix} 0 & 1 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 0 \end{bmatrix} \quad (6), \quad H_{bro} = \frac{1}{4}\begin{bmatrix} 0 & 1 & 0 \\ 1 & 1 & 0 \\ 0 & 1 & 0 \end{bmatrix} \quad (7)$$

The two low-pass filters, matrix (6) and (7), make up of the low-pass filter II in Fig.3. After being filtered by those two filters, R and B component arrays become smoother. So the compression ratio can be improved with a small quality loss.

Moreover, the perfect reconstruction can be gotten for high image quality. The reconstruction filters of equation (6) and (7) also have the impulse responses of equation (4) and (5) respectively.

Compared to the conventional compression method, only half size of G data and a quarter of R and B data need to be compressed in our method. So the complexity of hardware implementation of our method is much lower than that of the conventional.

C. Rounding Operation

Because in matrix (2), (6) and (7), there is an identical coefficient, *1/4*, the division operation or shift operation cannot be avoided. The residual value includes *0*, *1*, *2* and *3* for the implementation precision of low-pass filter I and II is *8*-bit. To reduce the residual error, the rounding operation of every filtered data can be described simply in the following equation(8).

$$y = \left\lfloor \frac{1}{4}(x+1) \right\rfloor \quad (8)$$

Here, ‘$\lfloor \bullet \rfloor$’ is the integer valued operator ($\lfloor \bullet \rfloor \le \bullet$). x and y are integers, and y is the rounded result.

D. Error Analysis

In this method, error is generated only by the division operation in the smooth filter I and smooth filter II because there is no loss in JPEG-LS.

The absolute error between the original CFA data and the filtered data is expressed in the following equation (9):

$$e_2 = \left| x - 4\times\left\lfloor \frac{1}{4}\times(x+1) \right\rfloor \right| \quad (9)$$

Here, x is an integer and e_2 is the absolute error between the original data and filtered data. From the equation (9), $e_2 \le 2$ is got. After the rounding operation, the maximum absolution error is reduced to two. Experimental results show the approximate probability distribution of e_2, $p(e_2)$, can be described as follows:

$$p(0) = p(2) = \frac{1}{4}, p(1) = \frac{1}{2}. \quad (10)$$

The error value is focused on one and zero after rounding operation. In order to accurately describe the error between the reconstructed data and original CFA data in theory, we can define PSNR as follows:

$$PSNR = 10\log_{10}\left(\frac{255^2}{\frac{1}{H\times W}\sum_{x=1}^{W}\sum_{y=1}^{H}(D_1(x,y)-D_2(x,y))^2} \right) \quad (11),$$

Where D_1 and D_2 are the original and reconstructed CFA data with height of H and width of W, respectively.

According to the error distribution equation(10) and PSNR equation(11), the PSNR can be got as follows:

1) When low-pass filter II isn’t used,

$$PSNR = 10\log_{10}\left(\frac{255^2}{\frac{1}{H\times W}\bullet\left[p(1)\bullet(\frac{H\times W}{4})\bullet 1^2 + p(2)\bullet(\frac{H\times W}{4})\bullet 2^2 \right]} \right) = 52.39$$

2) When low-pass filter II is used.

$$PSNR = 10\log_{10}\left(\frac{255^2}{\frac{1}{H\times W}\bullet\left[p(1)\bullet(\frac{H\times W}{2})\bullet 1^2 + p(2)\bullet(\frac{H\times W}{2})\bullet 2^2 \right]} \right) = 49.38$$

So, the PSNR of the reconstructed CFA data is about 52.39dB without low-pass filter II and is about 49.38dB with low-pass filter II in the proposed method, which assures the perfect reconstructed image quality

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

The performance of the presented method is evaluated by comparing it with other three compression methods as follows:

1) The ‘structure conversion’ method [3] presented by Koh, Mukherjee and Mitra.

2) The conventional lossless compression method.

3) The method of compressing CFA data directly.

In this experiment, the CFA raw data are generated from six standard 24-bit color test images with size *512×512* which includes ‘lena’, ‘baboon’, ‘airplane’, ‘house’, ‘lake’ and 'peppers'. The interpolated image without compression is regarded as the source image like the paper [2]. In the conventional lossless compression method, the interpolated images are compressed by JPEG-LS. For simplicity, the interpolation scheme is the bilinear method, but the proposed method can be applied to any interpolation. The comparison results of the following methods are shown in table I:

a) 'Proposed method with low-pass filter II': B and R components are filtered by low pass filter II.

b) 'Proposed method without low-pass filter II': B and R components are compressed directly by JPEG-LS encoder without low pass filter II.

c) 'Structure Conversion': It is realized according to the first method presented in the paper [3], and the structure conversion is not in YUV space but in RGB space for low computational complexity and high image quality.

d) 'JPEG-LS after interpolation': CFA data is interpolated into a full color image followed by JPEG-LS.

e) 'JPEG-LS for CFA data': CFA raw data is directly compressed via JPEG-LS.

The CPSNR and compression ratio of every image with CFA pattern are shown in Table I.

Among the compression methods in Table I, the proposed method can provide the highest compression ratio as well as very high CPSNR, which is larger than *51*dB with low pass filter II and larger than *57*dB without low-pass filter II. The low-pass filter II can bring about 6 dB quality loss and about 5% compression ratio gain. Moreover, when R and G components are compressed directly without filtering operation like the structure conversion method, not only compression ratio but also CPSNR of the proposed method are higher than that of structure conversion method. So the results prove that the proposed near-lossless compression method is very efficient.

In the structure conversion method, high frequency contents are still remained in the horizontal direction. But the low-pass filter I and II in the proposed method can reduce high frequency contents not only in the vertical direction but also in the horizontal direction. What's more, the errors in both methods are generated by the same operation, i.e., division *4*. There is no color space conversion in the proposed method and low pass filter I and II can be implemented only by shifts and adds. So the computational complexity of the method is much lower than the structure conversion method.

TABLE I

COMPRESSION RESULTS FOR TEST IMAGES

		airplane	baboon	house	lake	lena	peppers
Proposed method with low-pass filter II	CPSNR (db)	51.3113	51.4516	51.3647	51.3464	51.3357	51.4602
	Compression ratio	5.868:1	4.051:1	5.182:1	4.756:1	5.476:1	5.404:1
Proposed method without low-pass filter II	CPSNR (db)	57.2054	57.1977	57.218	57.2217	57.2119	57.4301
	Compression ratio	5.607:1	3.876:1	5.037	4.554:1	5.161:1	5.161:1
Structure conversion method	CPSNR (db)	55.8273	55.7578	55.7644	55.7893	55.6953	56.0396
	Compression ratio	5.462:1	3.813:1	4.950:1	4.466:1	5.036:1	5.062:1
JPEG-LS after interpolation	Compression ratio	1.794:1	1.336:1	1.636:1	1.514:1	1.613:1	1.640:1
JPEG-LS for CFA data	Compression ratio	4.609:1	3.175:1	3.838:1	3.503:1	3.223:1	3.121:1

The compression ratio = size of interpolated image / compressed size = 786432(bytes) / compressed size

TABLE II

COMPRESSION RESULTS OF PROPOSED METHODS WITH ROUNDING OPERATION AND WITHOUT ROUNDING OPERATION

	Image (512 × 512)	airplane	baboon	house	lake	lena	peppers
Proposed method with rounding operation	CPSNR(db)	51.3113	51.4516	51.3647	51.3464	51.3357	51.4602
	Compression ration	5.868:1	4.051:1	5.182:1	4.756:1	5.476:1	5.404:1
Proposed method without rounding operation	CPSNR(db)	47.9002	48.028	47.9165	47.9166	47.9032	48.0665
	Compression ration	5.827:1	4.048:1	5.155:1	4.749:1	5.446:1	5.398:1

The compression ratio = size of interpolated image / compressed size = 786432(bytes) / compressed size

IV. CONCLUSION

A novel near-lossless image compression for digital image sensors with Bayer CFAs has been presented. The experimental results show that the method not only has higher compression performance but also has lower complexity of hardware implementation than conventional image compression methods and other existing similar compression methods. This method is suitable for on-chip CFAs of digital image sensor with the requirement for high image fidelity such as medical video image compression area. In order to evaluate its validity, the proposed method is compared with structure conversion method in details. The reason that the proposed method is more efficient than conversion structure method is analyzed. Actually, this method can be used as a lossy image compression method with JPEG lossy compression or JPEG 2000 lossy encoder instead of JPEG-LS. Its lossy compression performance is also better than the conventional lossy compression method and structure conversion method.

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