

A Novel Method of Lossy Image Compression for Digital Image Sensors with Bayer Color Filter Arrays

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Abstract—Through the analysis of exist compression-first methods, this paper presents a novel method of lossy image compression for digital colorful image sensors with Bayer Color Filter Arrays (CFAs). In this method, an optimized compression and decompression structure is presented, and the captured CFA raw data is firstly low-pass filtered in RGB space by a smooth filter followed by the down-sampling operation. Then, the data are transformed from RGB space to YCbCr space. Lastly, the filtered data in YCbCr are compressed directly before full color interpolation that introduces redundancy. The presented method can provide lower compression ratio (bit/pixel) and lower complexity than conventional interpolation-first image compression methods and other existing similar compression-first methods.

Index Terms—Bayer CFA, low-pass filter, lossy image compression, and quincunx pattern.

I. INTRODUCTION

COLORFUL digital image sensors are applied in all kinds of video image areas. In most conventional applications of image sensors, the captured data with CFA pattern is interpolated into a full color image firstly and then the interpolated data is post-processed and compressed. The conventional interpolation-first method is shown in Fig 1(a). However, the redundancy is introduced before compression in this interpolation-first scheme. Several new methods based on the compression-first scheme shown in Fig.1 (b) have been reported to avoid the data redundancy by moving compression operation before color pixel interpolation [1-4].

It was demonstrated that using the compression-first scheme retains more pertinent information, thus lower compression ratio and higher image quality are achieved [1-4]. This paper also presents a new method for lossy compression based on the compression-first scheme of Fig 1(b). Several existing compression-first methods are analyzed in section II. The proposed method is described in detail in section III. Then the performance comparisons are discussed in section IV. Finally, the conclusion is given in section V.

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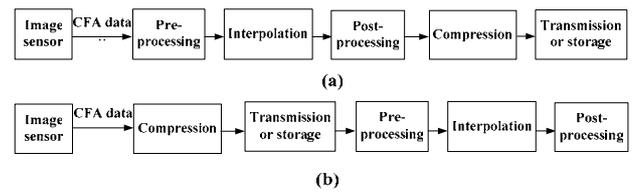


Fig. 1. Block diagrams of compressed schemes in a image sensor: (a) conventional interpolation-first method, interpolation before compression, (b) new compression-first method, interpolation after compression.

II. ANALYSIS OF EXISTING METHODS

Toi and Ohita applied the subband coding technique in the compression-first scheme [2]. A non-separable two dimensional diamond filter is used to process the quincunx green array. But the computational complexity is high.

Lee and Ortega [3] give a reversible image transformation. The RGB is transformed to YCbCr firstly. Then Y data array is rotated into a rhombus. And finally the rotated Y data and original Cb and Cr data are separately compressed by JPEG. However, the rotated Y data is not rectangular so that the standard encoder such as JPEG-LS cannot be applied directly.

Recently, Koh, Mukherjee and Mitra [4] present two new methods, ‘structure conversion’ method and ‘structure separation’ method. The structure conversion method can provide lower computational complexity as well as very good compression performance. But the CFA data is low-pass filtered in YCbCr space, which leads to image quality loss.

There are three different ways[2-4] to evaluate the validity of compression methods of CFA pattern image. Considering the evaluation standard in [3] is closer to the practical situation, this paper uses it as an evaluation standard. So, Composite Peak Signal to Noise Ratio (CPSNR), the measure of quality, is defined as follows:

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

Where I_1 and I_2 are the original interpolated and reconstructed full color image with height of H and width of W , respectively, and i represents the color plane.

III. PROPOSED IMAGE COMPRESSION METHOD

There are several different color filter arrays (CFAs), but

the Bayer CFA [5], as shown in Fig.2, is most popular in image sensors. Here the green filters are placed in a quincunx pattern, and red and blue filters are in the remaining locations. Note that there is only one color component in each pixel. The proposed method only considers the Bayer CFA, but it can be expanded easily to other CFAs. In this compression method, the implementation precision is 8-bit. It can also be expanded to other precision.

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

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

A. Method Structure

Unlike other methods [3][4], an optimized compression and decompression structure illustrated in Fig.3 is used in the presented method. CFA raw data is firstly processed by a low-pass filter in RGB space instead of YCbCr space because the correlation of neighborhood pixels in RGB space is stronger than that in YCbCr space. The lossy compression method structure is shown in Fig.3(a). The transformation from RGB space to YCbCr space in this method is as same as that in the Ref[3][4]. There is no low-pass filter for R and B components in lossy compression method structure for the shape of R and B components is rectangle. The corresponding decompression structure is illustrated in Fig.3(b). There is no reconstruction filtering operation in decompression because the correlation between neighborhood pixels becomes very weak after lossy compression. So, the proposed decompression structure is not only much simpler but also has much better decompression performance than that of 'structure conversion' method[4]. For low complexity, JPEG is used in this method.

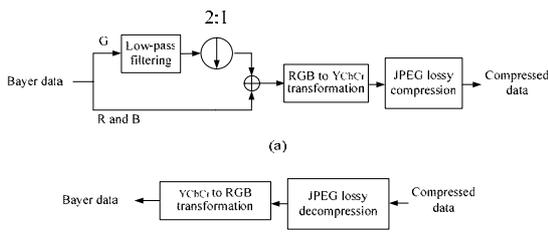


Fig.3. Block diagrams: (a) lossy compression structure for CFA data, and (b) lossy decompression structure for CFA data.

B. Method Description

The proposed compression consists of low-pass filtering, down-sampling, color space conversion and JPEG.

1) Filtering and down-sampling operation.

There are more high frequency components in the horizontal direction and vertical direction of the Bayer CFA data than that of 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 should be low-pass filtered firstly. After filtering operation, the smoothed data is remained and the original raw data are removed to keep the data quantity unchanged by the

down-sampling (2:1) operation. At the same time, the down-sampling operation implements the transformation operation of G component from quincunx to rectangular array.

In this paper, two different low-pass filters and an optimized structure conversion method are also given.

The first filter has the following impulse response array in equation(3).

$$H_{cg1} = \frac{1}{4} \begin{bmatrix} 0 & 1 & 0 \\ 1 & 4 & 1 \\ 0 & 1 & 0 \end{bmatrix} \quad (3)$$

The filtering and down-sampling are described in Fig.4. The 8×8 size of CFA data is assumed, where pixels '●' and '○' represent original pixels of odd columns and even columns respectively. Pixel '○' represents the pixel which is generated from the original blank point, i.e., smoothed by the low-pass filter I. '○' 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 the blank points to get pixels '○' 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. Those down-sampled columns are emerged into a rectangular shape, which is the transformation operation of G component from quincunx to rectangle. The smooth filter reduces high frequency contents not only in the vertical direction but also in the horizontal direction.

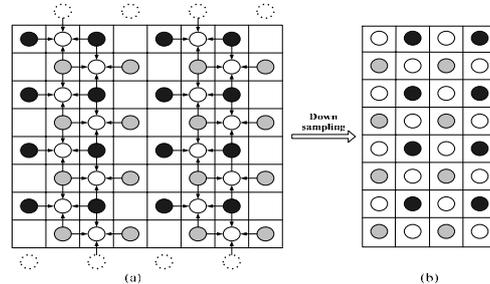


Fig.4. Smooth filtering and down-sampling operation of the first filter.

Because it is a reversible filter, the first filter can be reconstructed perfectly.

The second filter uses the following impulse response array in equation(4).

$$H_{cg2} = \frac{1}{4} \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \quad (4)$$

The filtering and down-sampling operation can be described in Fig.5. The 4×4 size of CFA raw data is assumed, where pixels '●' represent original pixels and pixels '○' represent the filtered pixels which are generated from the original blank point, i.e., smoothed by the low-pass filter. Pixels '○' represent the virtual pixels which are used to compute the boundary pixels in the filtering operation. The virtual pixels of upper boundary and left boundary are got from the first even row and the first even column respectively, i.e., the second row and the second column. The virtual pixels of bottom and

right boundary are equal to the original pixels of the second last row and the second last column respectively. In this method, the smooth filter is applied to the blank points to get pixels ‘○’ firstly, and then down-sampling operation is followed to removed the original pixels ‘●’. Those down-sampled pixels are lastly emerged into a rectangular shape, which is the transformation operation of G component from quincunx to rectangle. The low-pass filter reduces high frequency contents not only in the vertical direction but also in the horizontal direction, which can improve the compression performance.

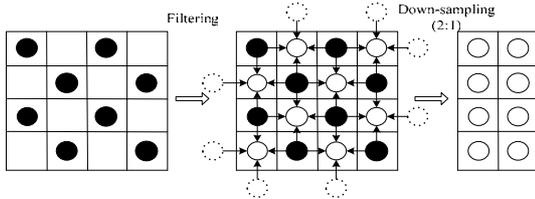


Fig.5. Filtering and down-sampling operations of the second filter.

In the optimized conversion structure method, the structure in Fig.4 is used, other operations of the optimized method are as same as that of structure conversion method[4]. The differences between them are that in the optimized structure conversion method, the filtering operation is executed in RGB space not in YCbCr space and there is no reconstruction filter unlike structure conversion method. The impulse response array of the low-pass filter is shown in equation (5). This filter is named the third filter in this paper.

$$H_{cg3} = \frac{1}{4} \begin{bmatrix} 0 & 0 & 1 \\ 0 & 2 & 4 \\ 0 & 0 & 1 \end{bmatrix} \quad (5)$$

2) Color space conversion

In the Bayer pattern, there are insufficient pixels to carry out the color space conversion for each point. Thus, this conversion is implemented on blocks of four pixels [6] as illustrated in Fig.6.



Fig.6. Blocks of four pixels used in the color space conversion.

The equation of color space conversion is illustrated in the following:

$$\begin{bmatrix} Y^{ul} \\ Y^{lr} \\ Cb \\ Cr \end{bmatrix} = \begin{bmatrix} a_{11} & 0 & a_{13} & a_{14} \\ 0 & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{31} & a_{33} & a_{34} \\ a_{41} & a_{41} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} G^{ul} \\ G^{lr} \\ B \\ R \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 128 \\ 128 \end{bmatrix} \quad (6)$$

Here, a_{31} and a_{41} are half of standard coefficients RGB to YCbCr conversion and the others are the same.

Lastly, those rectangular data are compressed by JPEG-LS. Compared to the conventional interpolation-first 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 interpolation-first methods. Three filters used in this compression method, H_{cg1} , H_{cg2} , and H_{cg3} , have same computational complexity which is as same as structure conversion[4] and much lower than that of other compression methods in Ref [2][3] and structure separation[4].

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

In this experiment, the CFA raw data are generated from the standard 24-bit color test images with size 512×512 which includes ‘lena’ and ‘baboon’. The interpolated image without compression is regarded as the source image in this experiment. The Fig.8 shows the comparison of three different structure conversion compression methods as follows.

1) Optimized structure conversion: This method uses the new compression and decompression structure in Fig.4 and the low-pass filter of conversion structure[4].

2) Optimized structure conversion in YCbCr space: The new compression structure in Fig.4 and the low-pass filter of conversion structure [4] are used.

3) Structure conversion in the Ref [4].

As seen in Fig.7, at the same compression ratio, the new compression and decompression structure can bring obvious gain in image quality because the optimized structure conversion have much better compression performance than the structure conversion. The reason is that the correlation between neighborhood pixels becomes very weak after lossy compression. The comparison between optimized structure conversion in RGB space and optimized structure conversion in YCbCr space shows the new compression structure can lead to a gain of compression performance at low compression ratio(up to 30:1).

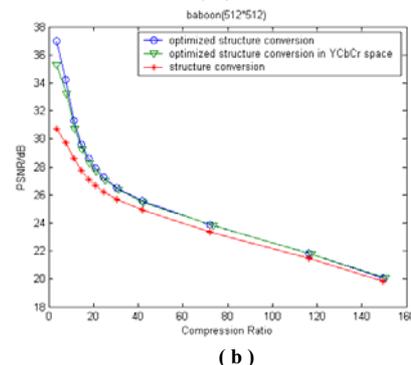
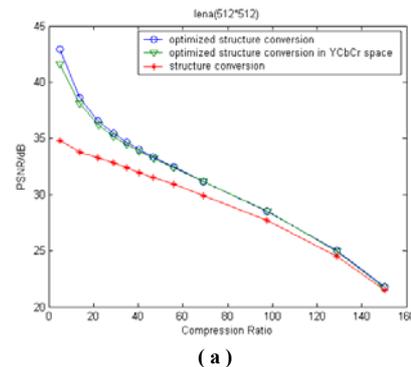


Fig.7. CPSNR vs. compression ratio of three different structure conversion methods: (a) lena image, (b) baboon image.

The comparison of five compression methods is illustrated in Fig.8. These methods include: 1) New method with the 1st filter: It uses the first low-pass filter, H_{cg1} , 2) New method with the 2nd filter: It uses the second low-pass filter, H_{cg2} , 3) Optimized structure conversion, 4) Structure conversion and 5)

Conventional interpolation-first method: The interpolation full color image is compressed via JPEG.

From this figure, the new method with the 2nd filter and optimized structure conversion method with the 3rd filter have better compression performance than structure conversion and conventional interpolation-first method at all the range of compression ratio (up to 140:1). The second filter (H_{cg2}) and the third filter (H_{cg3}) also have better compression performance than that of the first filter (H_{cg1}). At the same low compression ratio, i.e., up to 28:1 for lena image and up to 10:1 for baboon image, the third filter has better image quality than the second filter. When the compression ratio becomes large, the second filter owns better compression performance than the third filter.

The new method with the 1st filter has better compression performance than structure conversion. Its compression performance depends on the image frequency context. The compression performance gets better than the conventional interpolation-first method when the image contains more high frequencies just like in baboon image. In addition, its compression performance gets better than that of the conventional interpolation-first method when the compression ratio becomes large. Furthermore, the third filter can be used for near-lossless or lossless compression when the JPEG-LS replaces JPEG in the compression structure illustrated in Fig.4(a), and this filter has better compression performance than the other two filters.

Through above analysis, the first filter is suitable for the system in which the near-lossless, lossless and lossy are all needed, such as high quality image communication and medical image compression. The second filter and the third filter can only be used in a lossy image compression system.

V. CONCLUSION

A novel method for lossy image compression for digital image sensors with Bayer CFAs has been proposed. In this method, an optimized compression and decompression structure is applied and can lead to higher image quality at the same compression ratio. In addition, two new low-pass filters and optimized structure conversion are also presented for the new structure. The experimental results show that the proposed method using three different low-pass filters respectively has higher compression performance than conventional interpolation-first compression methods and structure conversion method. It also has lower complexity of hardware implementation than conventional interpolation-first compression methods and other existing similar compression-first methods. Due to its low complexity and good compression performances, the presented lossy compression method is suitable for on-chip CFAs of digital image sensors.

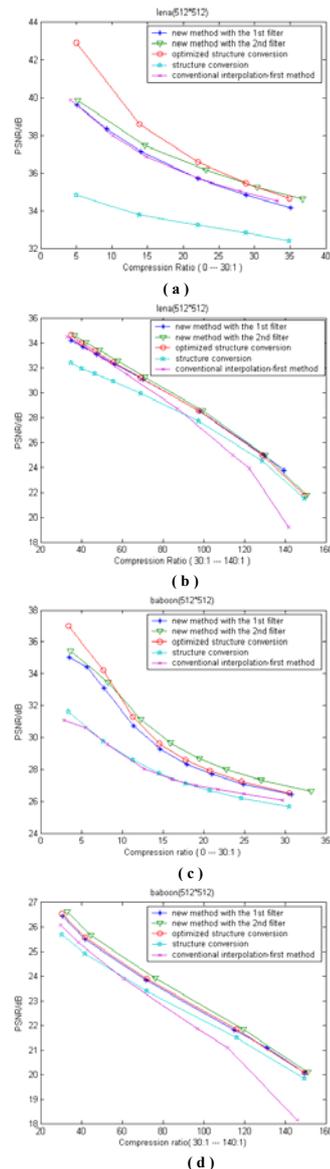


Fig.8. CPSNR vs. compression ratio of five different compression methods: (a) lena with compression ratio up to 30:1, (b) lena with compression ratio from 30:1 to 140:1, (c) baboon with compression ratio up to 30:1, (d) baboon with compression ratio from 30:1 to 140:1.

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